



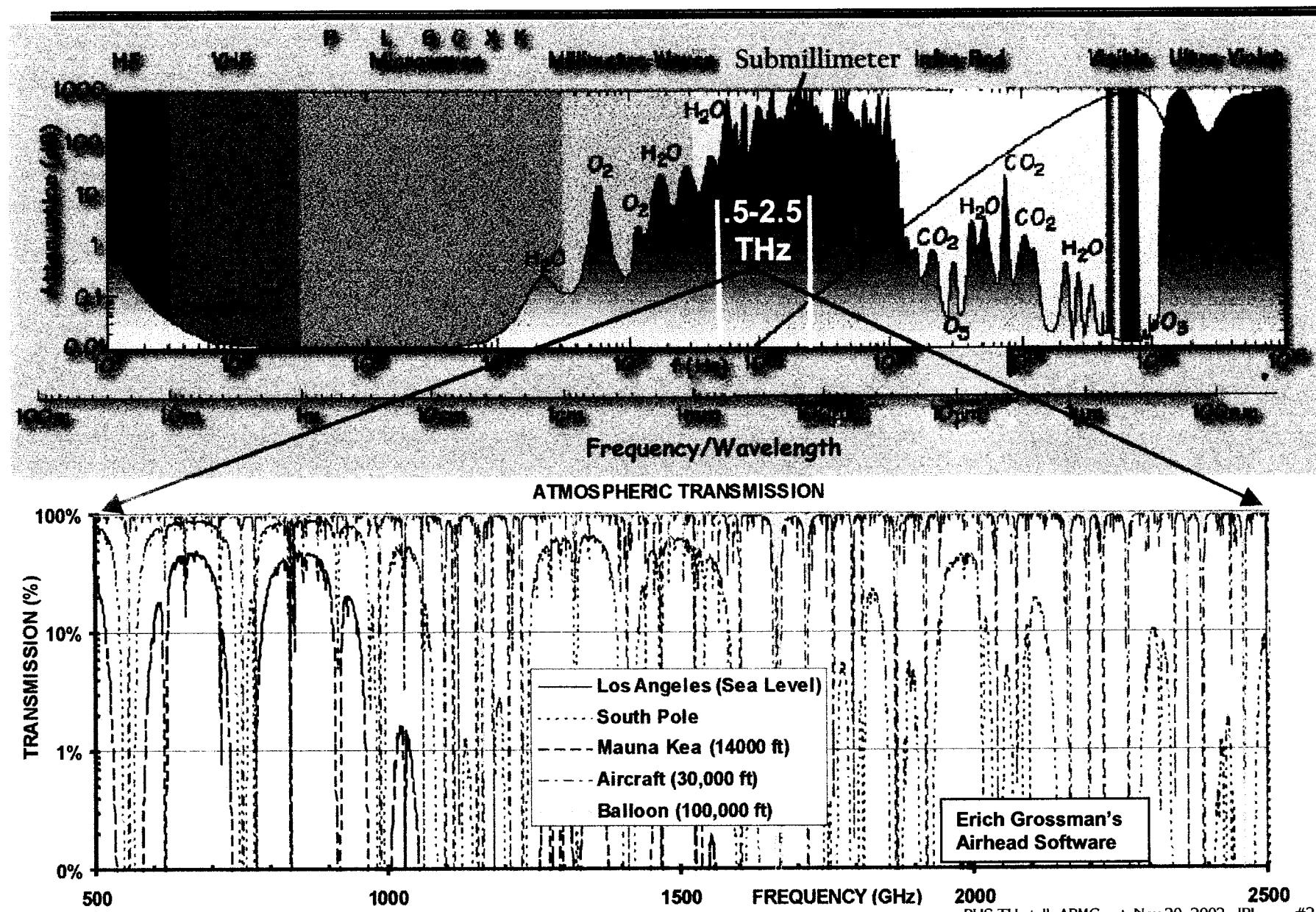
## THz Technology Applications Introduction



### TERAHERTZ TECHNOLOGY AND APPLICATIONS

*Asia Pacific Microwave Conference November 20<sup>th</sup>, 2002*

- Despite great scientific interest since at least the 1920's, the THz frequency range remains one of the least tapped regions of the electromagnetic spectrum.
- Sandwiched between traditional microwave and optical technologies where there is a limited atmospheric propagation path, little commercial emphasis has been placed on THz systems. This has, perhaps fortunately, preserved some unique science and applications for tomorrow's technologists.
- For over 25 years the sole niche for THz technology has been in the high resolution spectroscopy and remote sensing areas where heterodyne and Fourier transform techniques have allowed astronomers, chemists, Earth, planetary and space scientists to measure, catalog and map thermal emission lines for a wide variety of lightweight molecules.
- As it turns out, no where else in the electromagnetic spectrum do we receive so much information about these chemical species. In fact, the universe is bathed in THz energy, most of it going unnoticed and undetected.





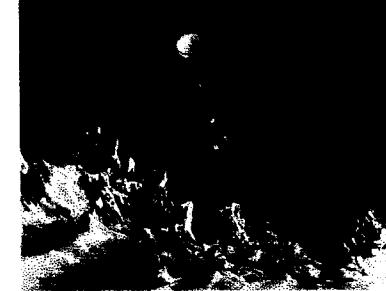
High Altitude Balloon



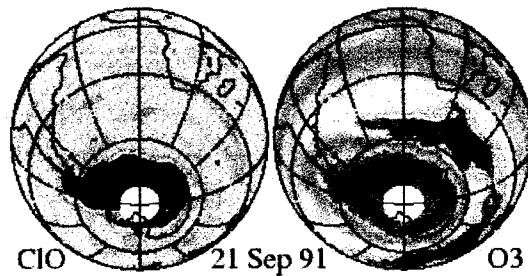
Airborne Platform (DC8/SOFIA)



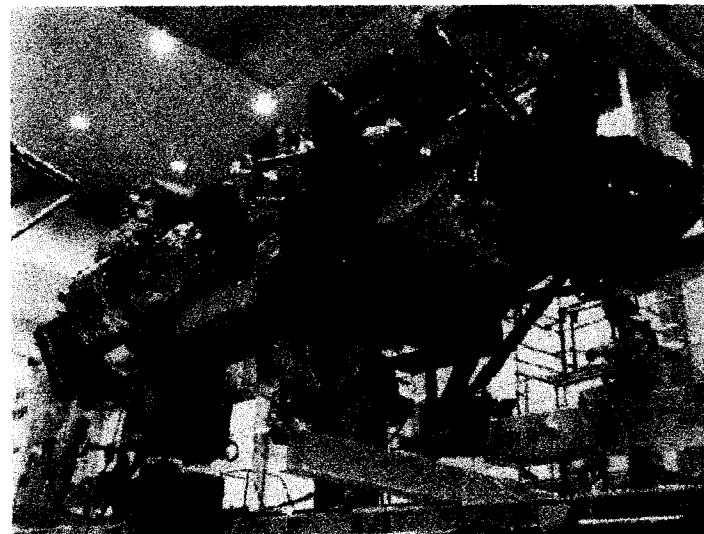
Earth Orbiter/Sounder



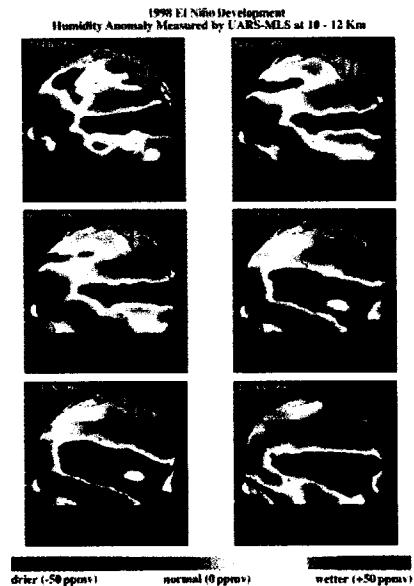
Planetary Sounder

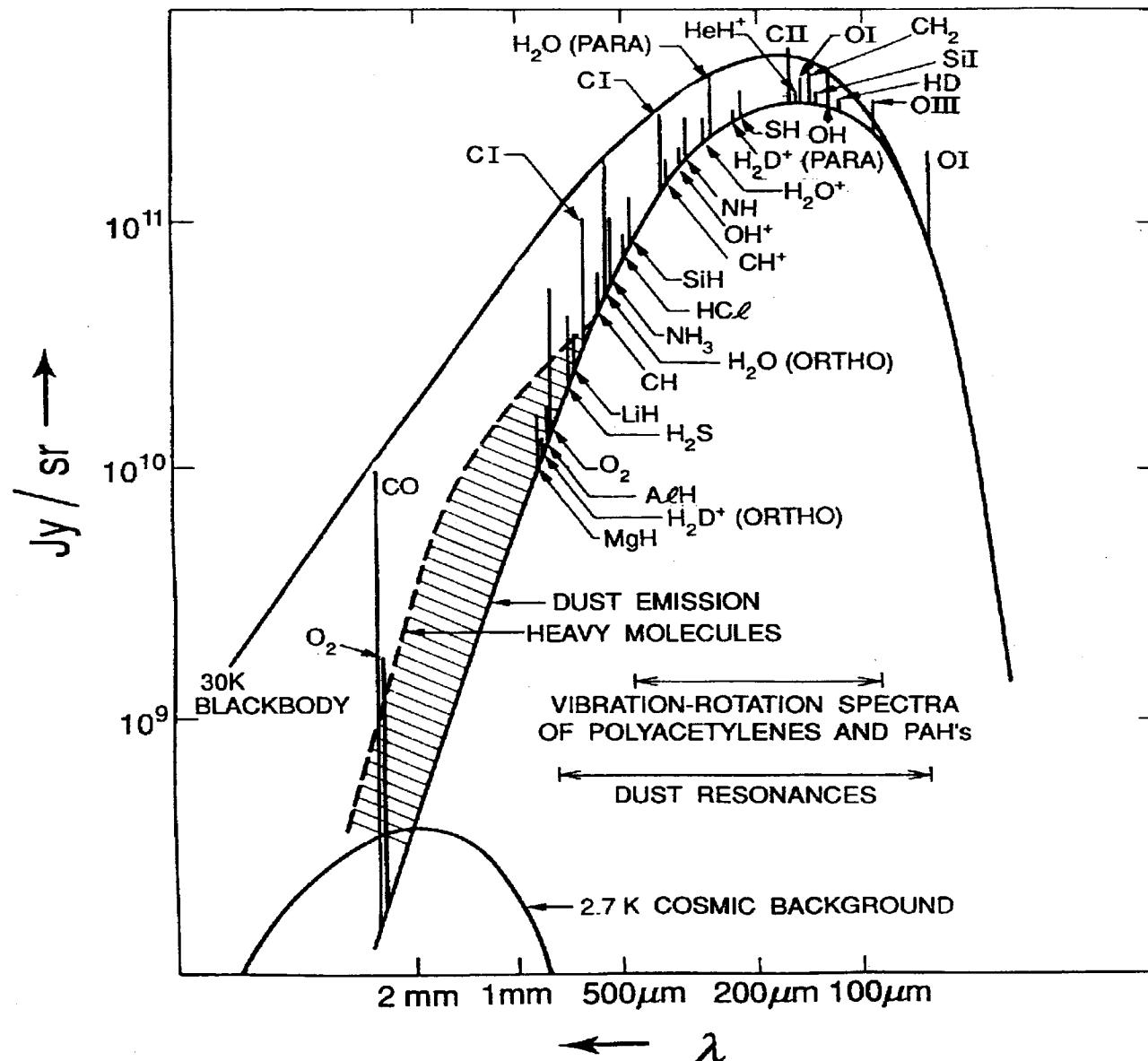


First UARS-MLS measurement  
of correlation between ozone  
depletion and chlorine enhance-  
ment from September 1991.



NASA's Upper Atmospheric Research Satellite

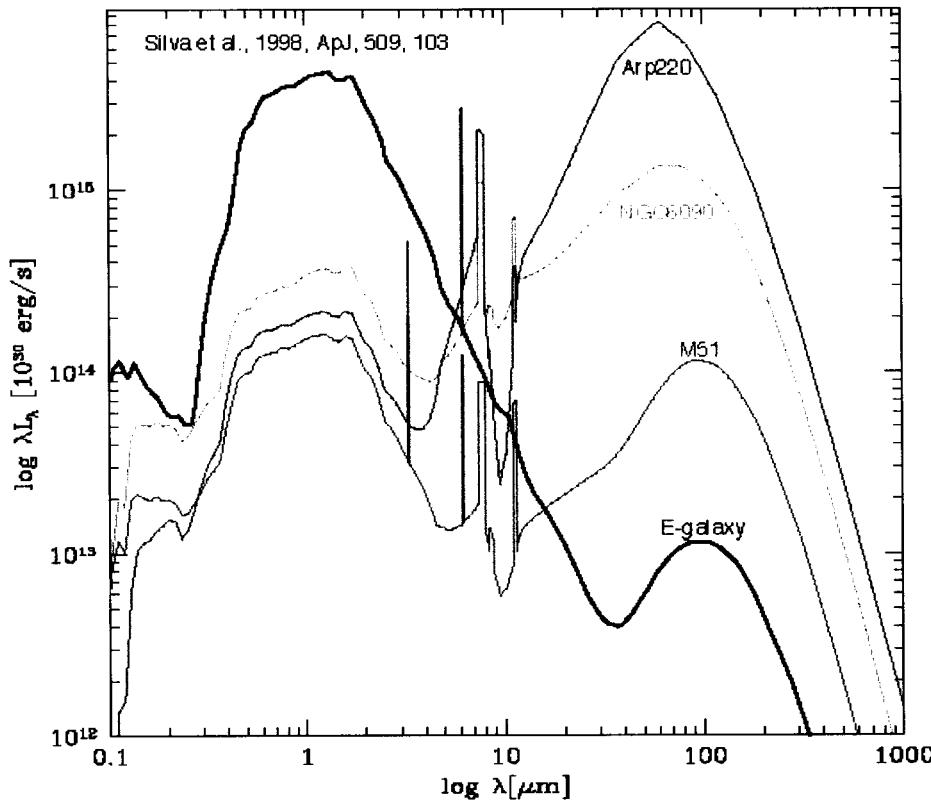
Water vapor during 1997  
El Nino from UARS-MLS



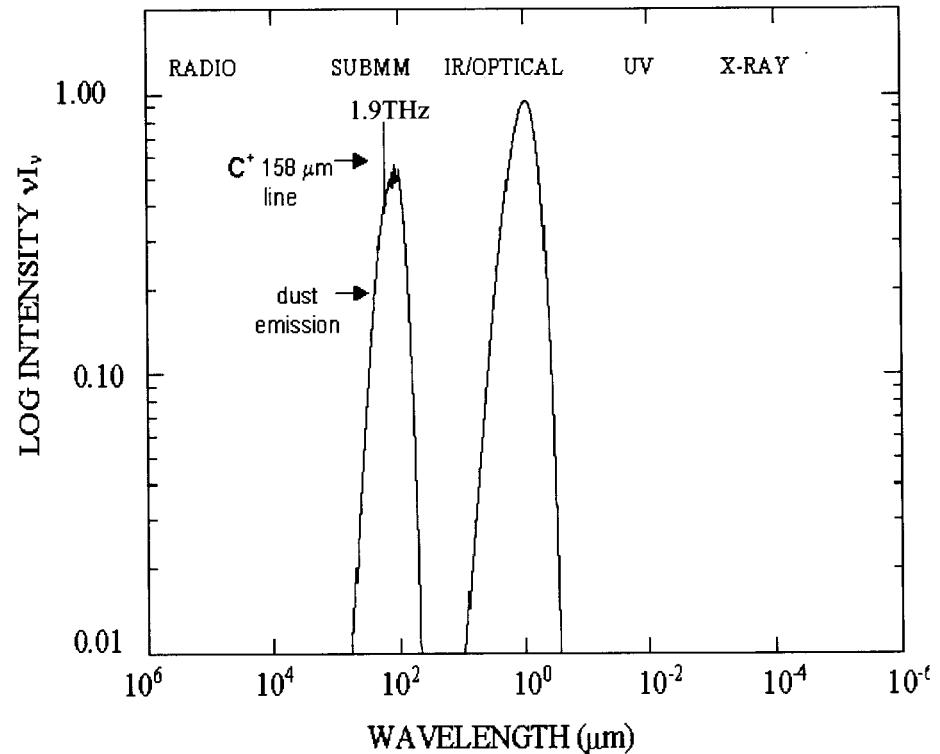
**Far-IR/submm is the primary band for line and continuum radiation from cool (5-100 K) gas (atoms and molecules) and dust**

**LEFT:**  
Radiated Energy vs.  
Wavelength showing  
30K blackbody,  
interstellar dust and  
key molecular line  
emissions (from Tom  
Phillips, IEEE Proc.,  
80, no. 11, 1992).

Half the luminosity and 98% of the photons released since the Big Bang are in the Submm/Far IR

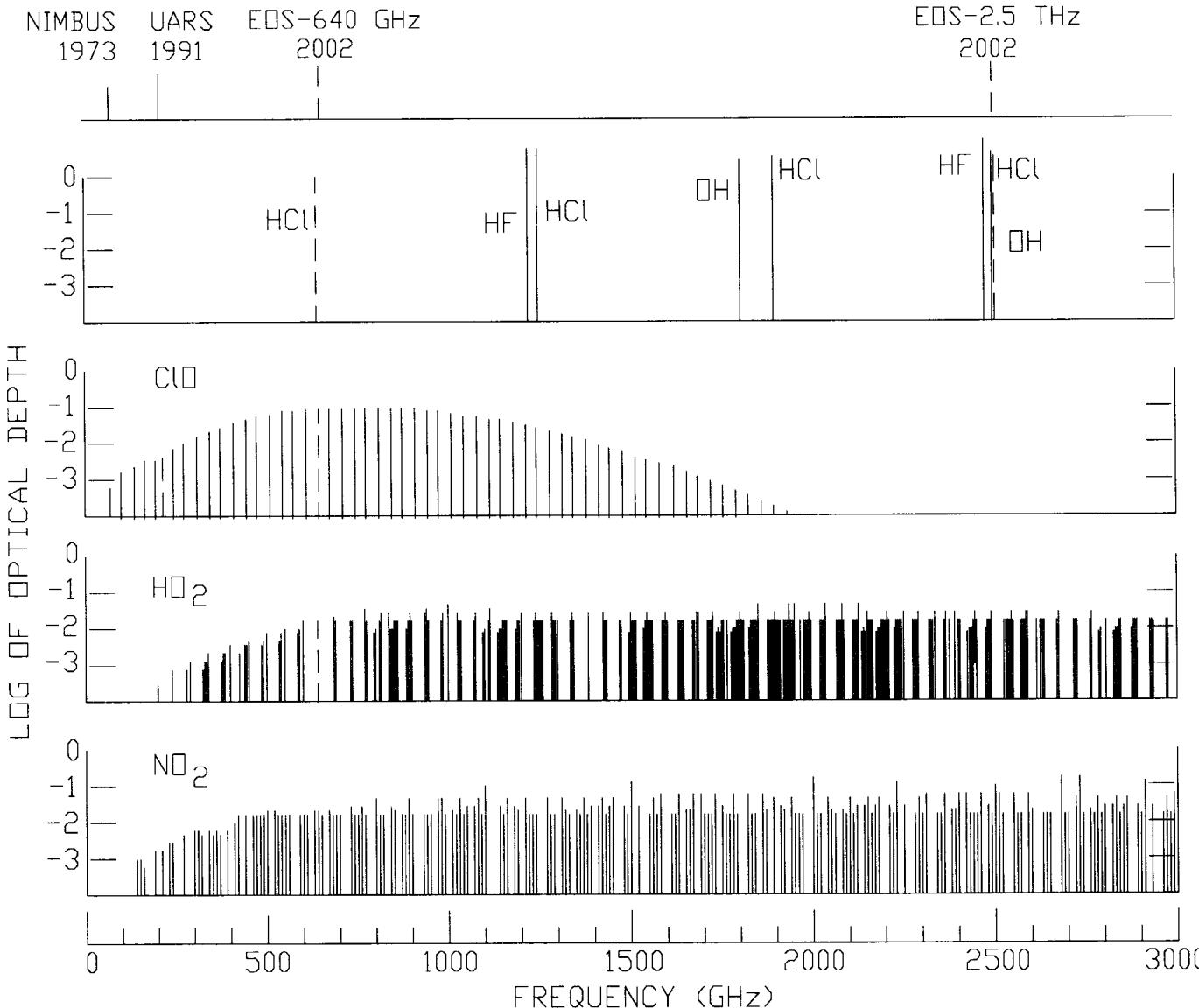


Energy output vs. wavelength for galaxies of ascending ages showing advantages of THz detection for probing the early universe  
(Courtesy Bill Langer – Herschel Sp. Obs. Archives)



Spectrum of Milky Way galaxy showing luminous power output vs. wavelength. Almost 50% of the power is emitted at THz frequencies!  
(From D. Leisawitz, SPIE Proc., 4013, Mar 2000)

## Heterodyne Technology for Earth Remote Sensing



Spectra of some important molecules in the Earth's upper atmosphere and measurements being addressed by NASA heterodyne instruments. The peak power or minimum frequency for many emission lines occurs in the THz region.  
(From: J. Waters, EOS Atmospheres presentation, Goddard Space Flight Center, 1991)

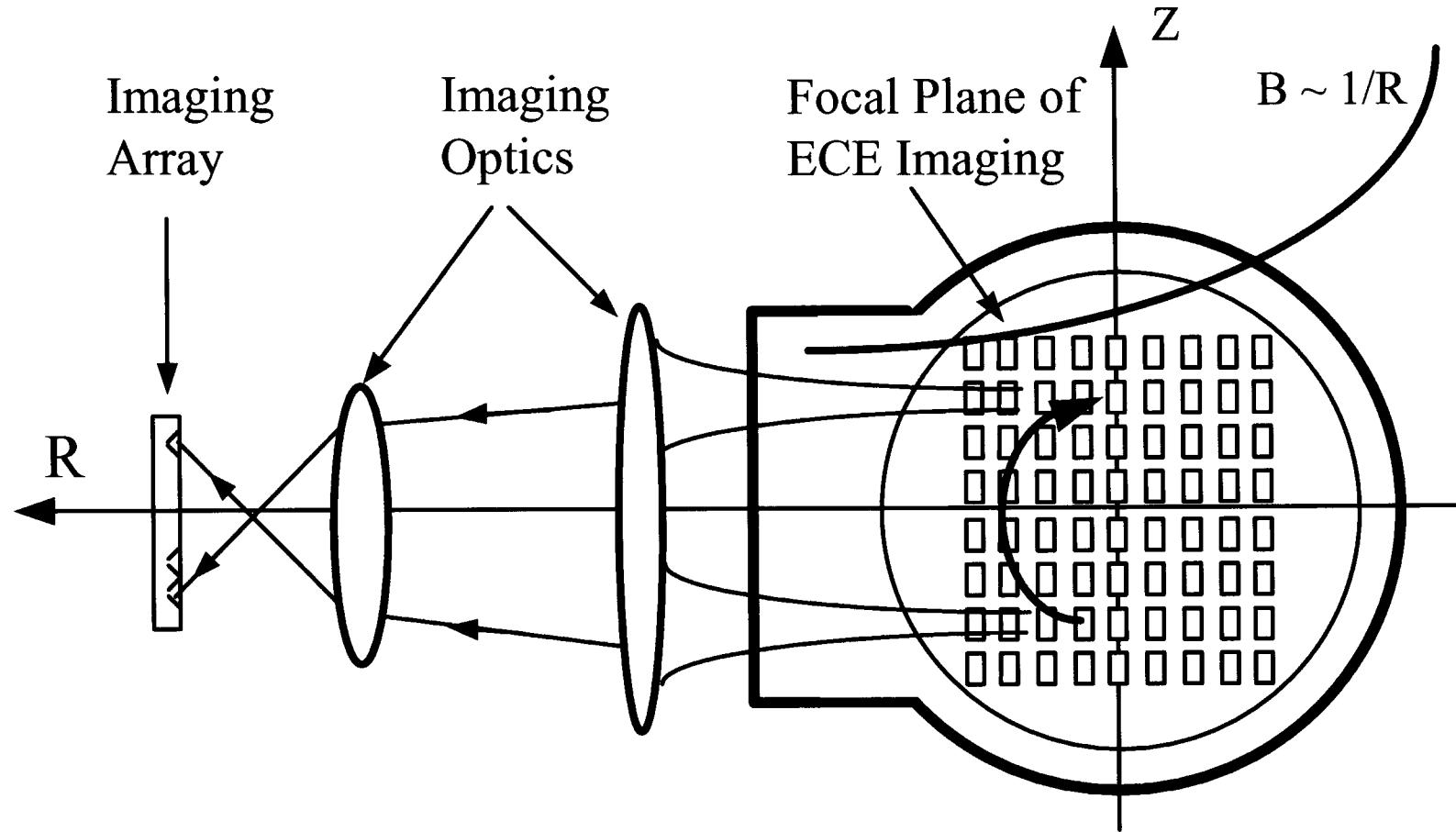
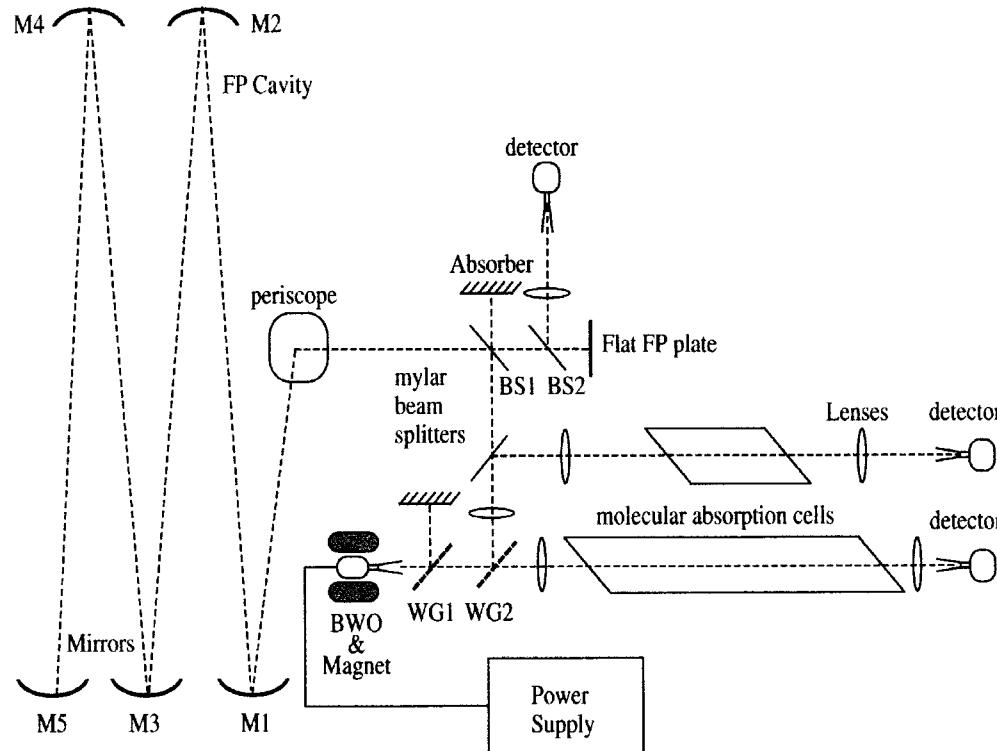


Diagram of 2D plasma ECE heterodyne imager using linear array of receive antennas for  $\sim 100$  GHz. LO power is incident from the rear of the array and distributed to each element by a cylindrical mirror.

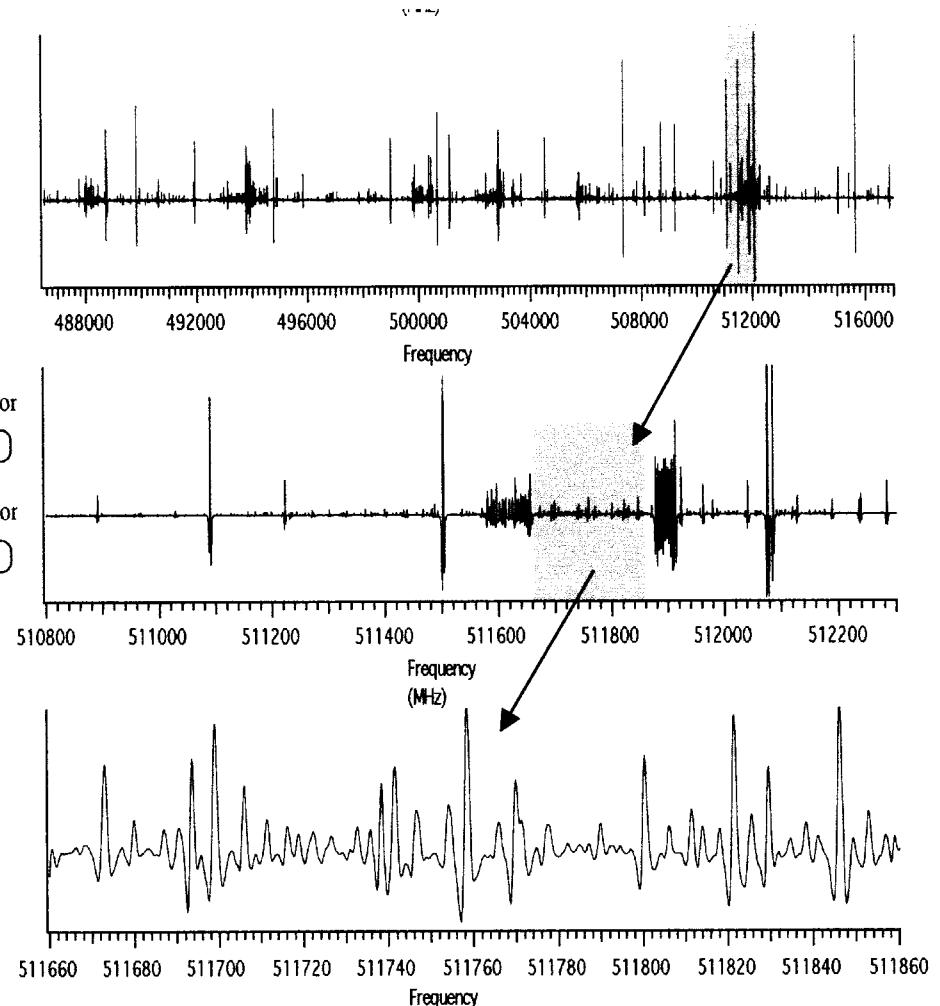
From Deng, Domier & Luhmann, Rev. Sci. Inst., 72, no.1, Jan. 2001).

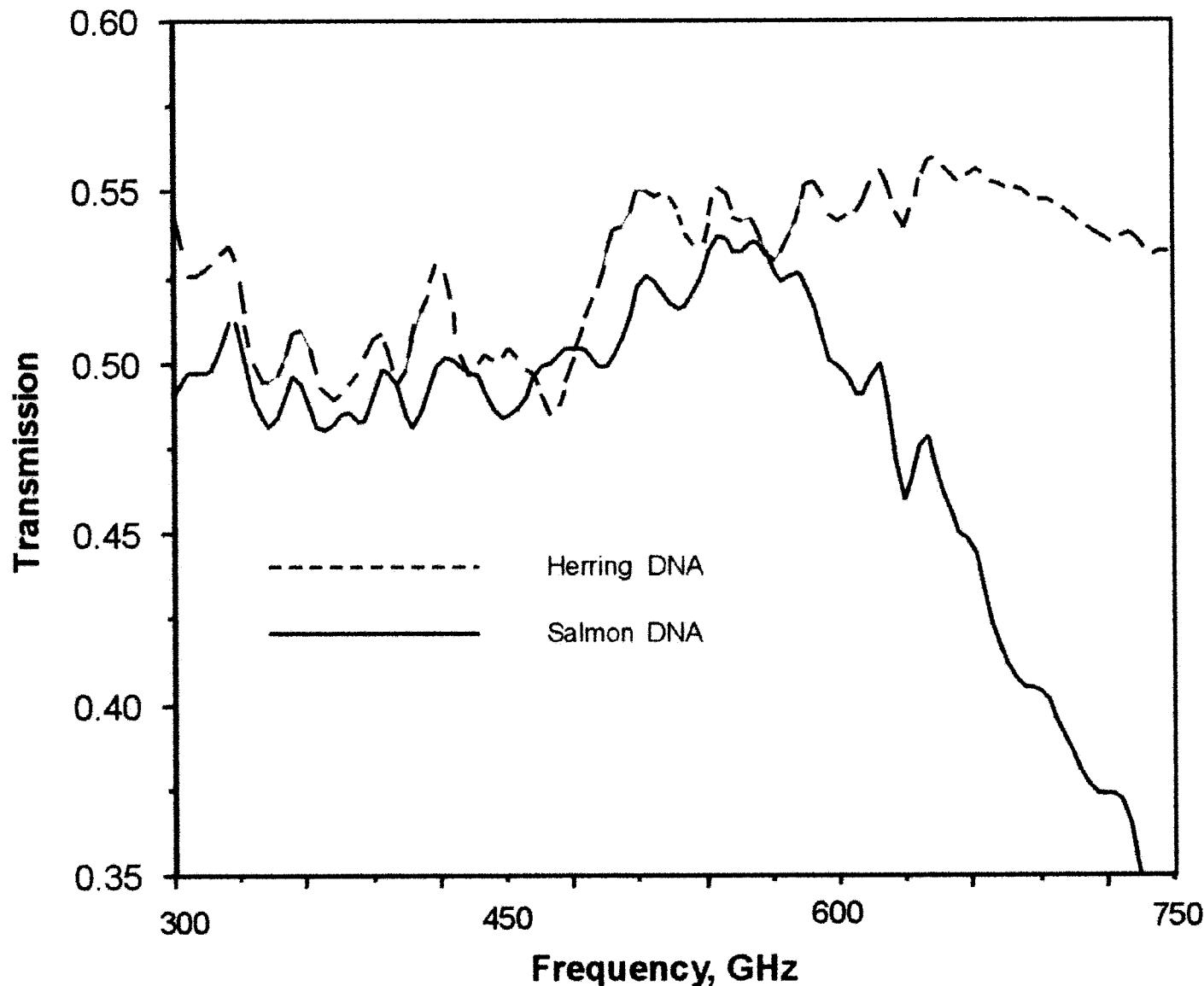


# THz Technology Applications Scanned Fourier Transform Spectroscopy System

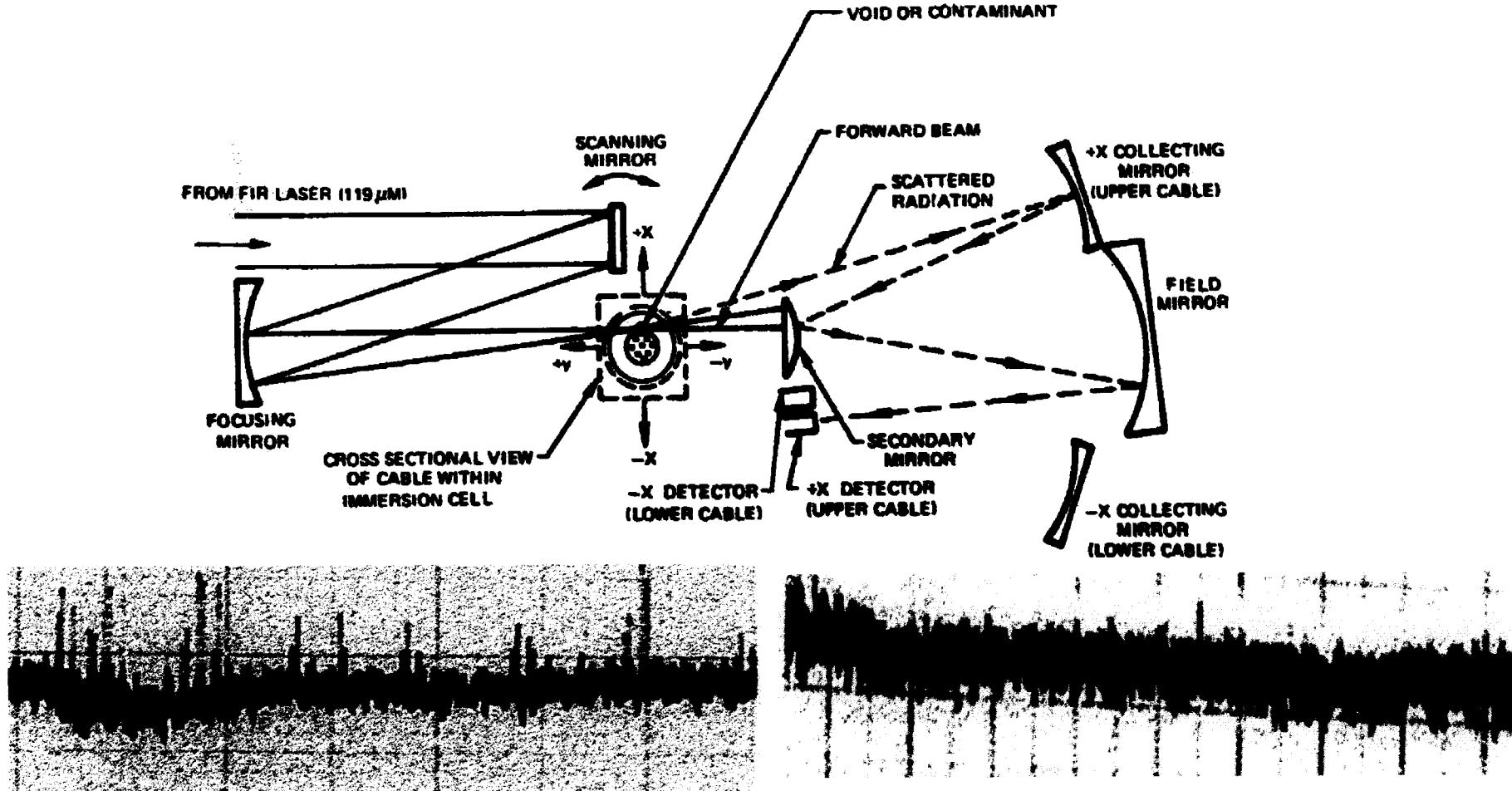


FAst-Scan Submillimeter Spectroscopic  
Technique FASSST (top) and spectral plots at  
500 GHz (right) in increasing frequency  
resolution sweeps (top to bottom) for a  
combination of pyrrole, pyridine and sulfur  
dioxide at 10mTorr each. From DeLucia & Albert,  
SPIE Proc., v. 3465, San Diego, CA, 1998).

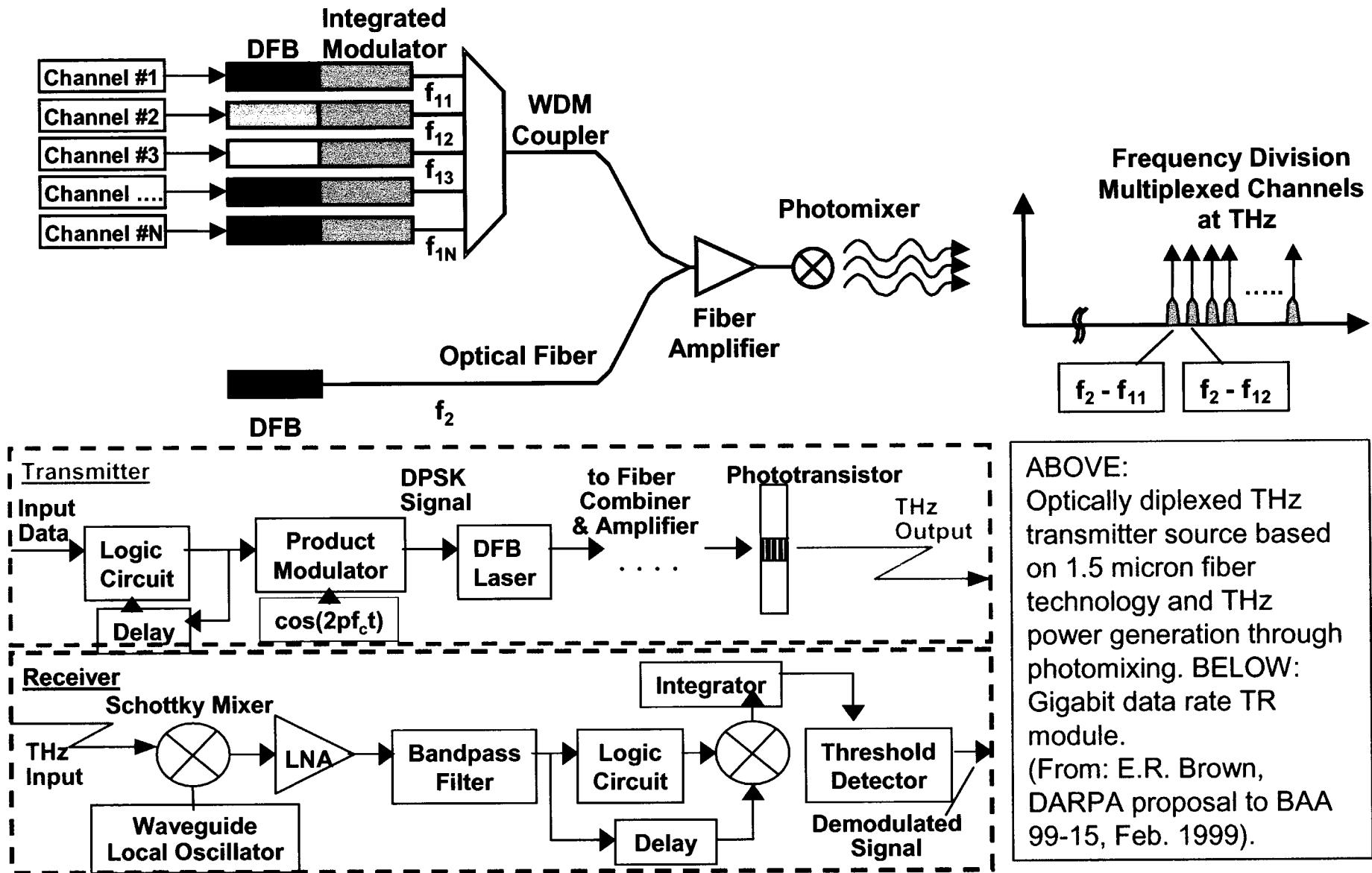


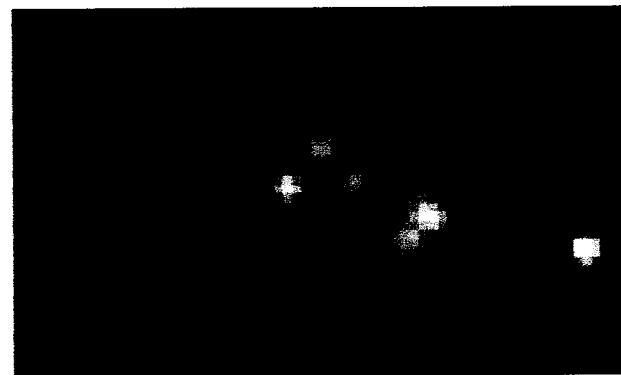
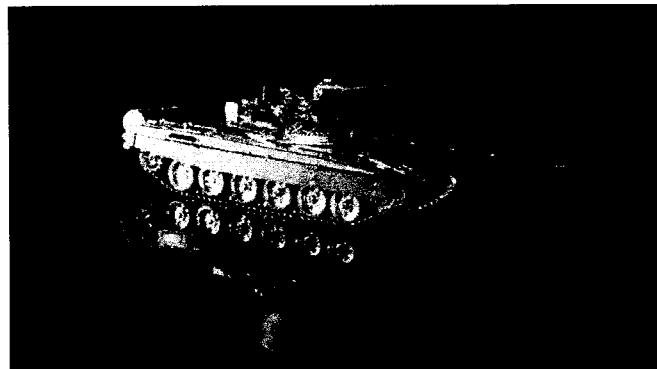
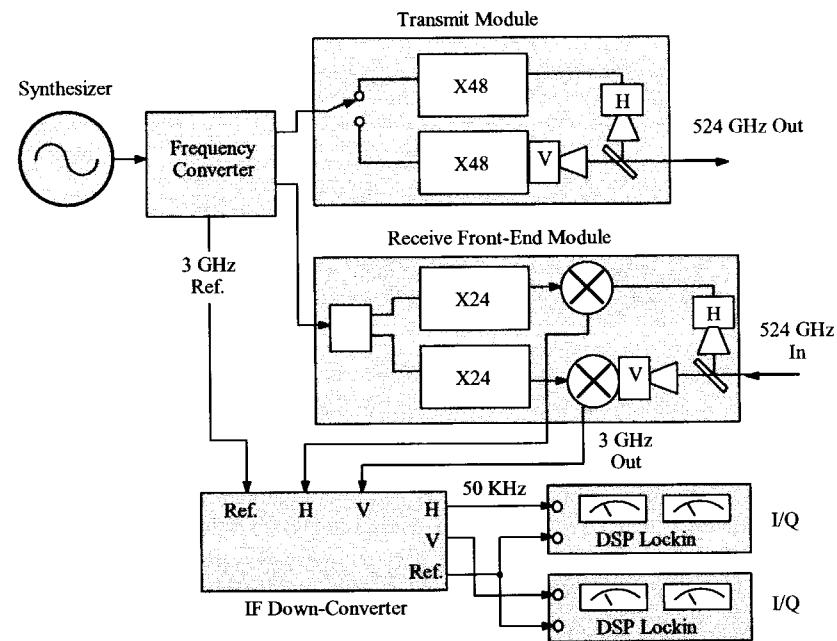
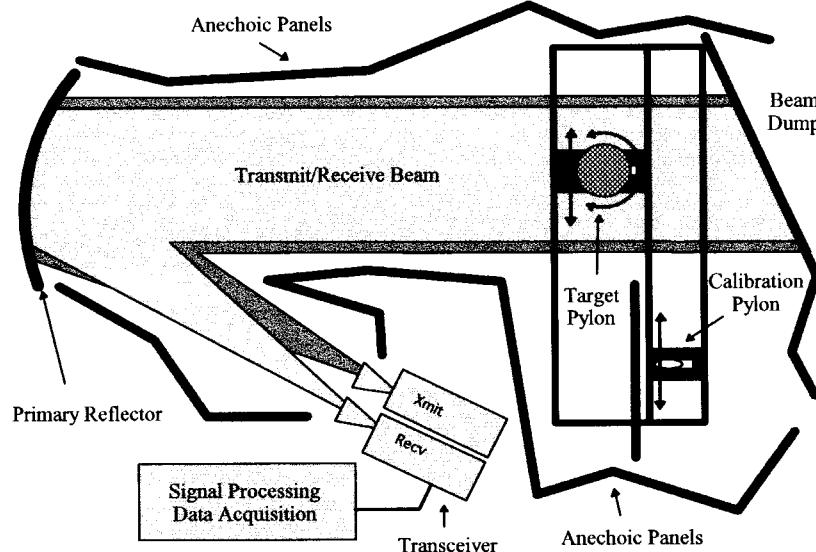


Comparison of Herring and Salmon DNA transmission spectra using an FTS system.  
(From D. Woolard et.al., 22<sup>nd</sup> Army Science Conf., Baltimore, MD, Dec. 2000).

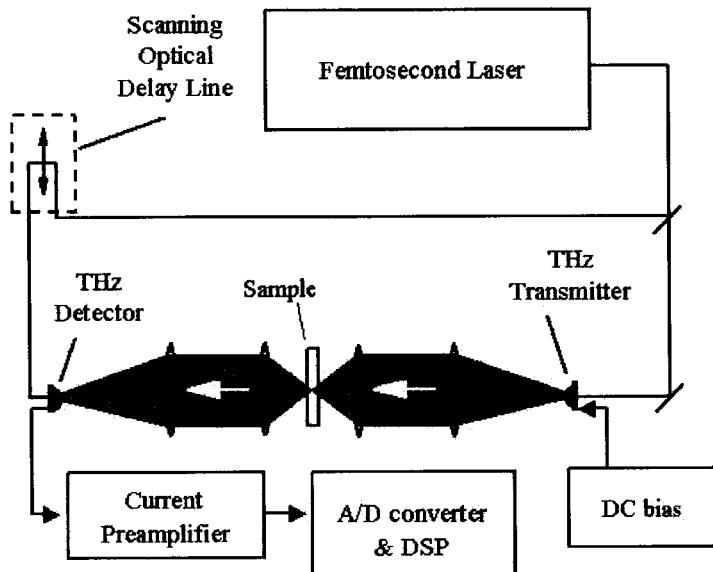


2.5 THz cable void inspection system and plots of scattered power from voided (left) and solid (right) cable. Peaks are indicative of void size. (From: Cantor, Cheo, Foster & Newman, IEEE J. Quantum Elec., QE-17, no. 4, April 1981).

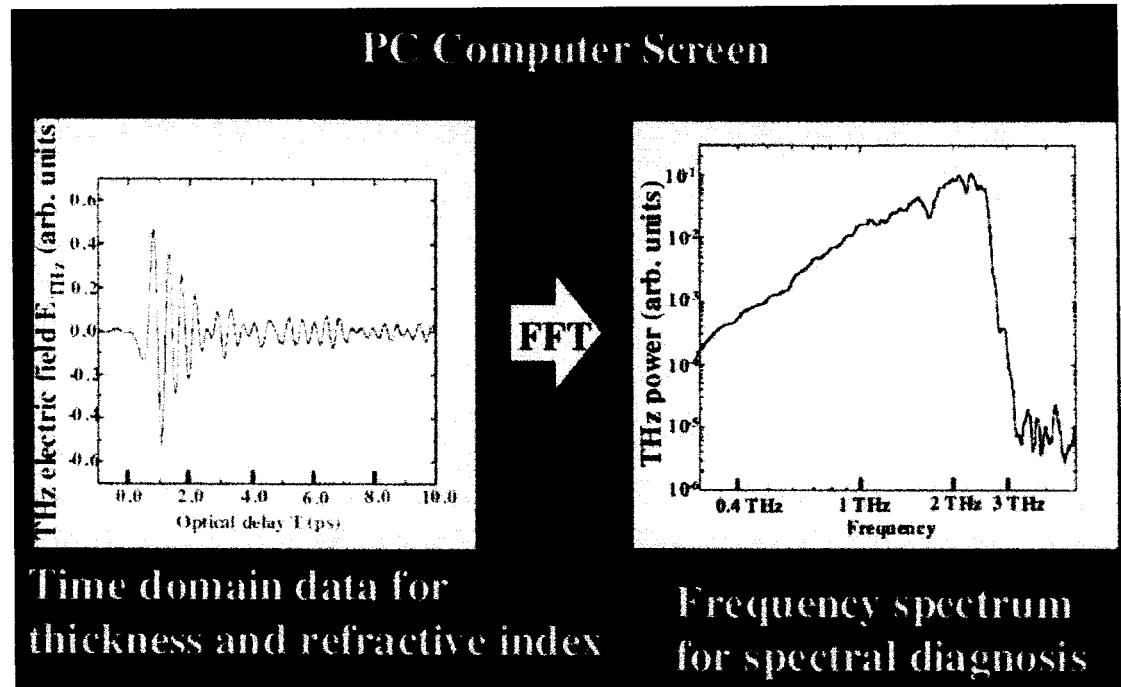




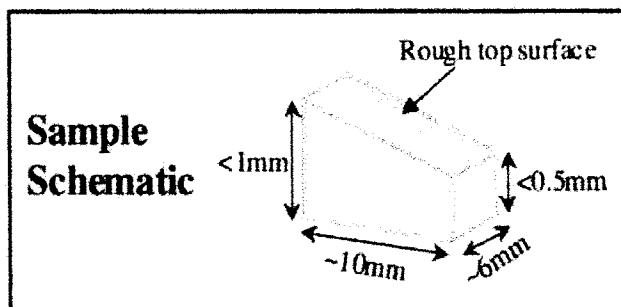
THz radar cross section system at Univ. of Lowell. Top left: Compact range layout and submillimeter transmit/receive arrangement. Top right: Transceiver block diagram. Bottom left: Optical image of scale model tank. Bottom right: Processed submillimeter wave radar image—cross section of 3D image. (From Coulombe et.al. Proc. AMTA, Monterey, CA, Oct. 1999).



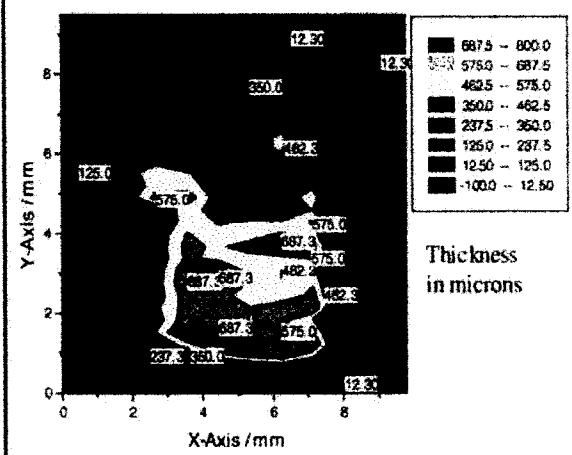
T-Ray imager schematic.  
 (From Dan Mittleman, R. Jacobson & M. Nuss, IEEE J. Selected Topics in Quantum Electronics, v.2, no.3, Sept. 1996).



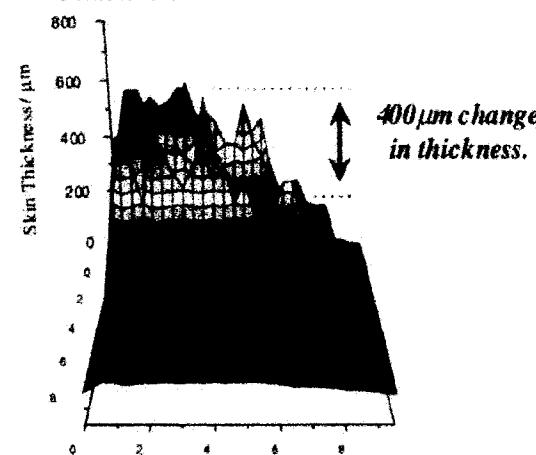
T-Ray data showing field versus optical delay (time domain) and Fourier transformed frequency domain spectral content.  
 (From Don Arnone et.al. , Proc. SPIE, vol. 3823, Munich, Germany, 1999).



**2D Contour Image of Thickness Variations.**



**3D Image of Thickness Variations.**



T-Ray 2D and 3D images showing capability of the technique to measure small variations in thickness at discrete points in a thin pork skin sample.

(From Don Arnone et.al. , Proc. SPIE, vol. 3823, Munich, Germany, 1999).

**Figure 9. 3D Tomographic TPI Image of Variations in Skin Thickness Across a Pork Skin Sample.**

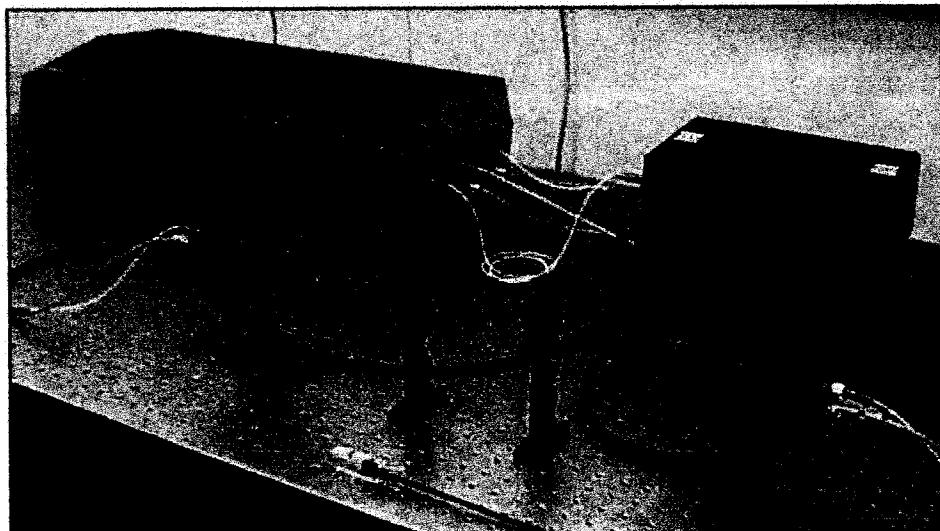


# THz Technology Applications

## T-Ray Imaging Application & 1<sup>st</sup> Commercial Product

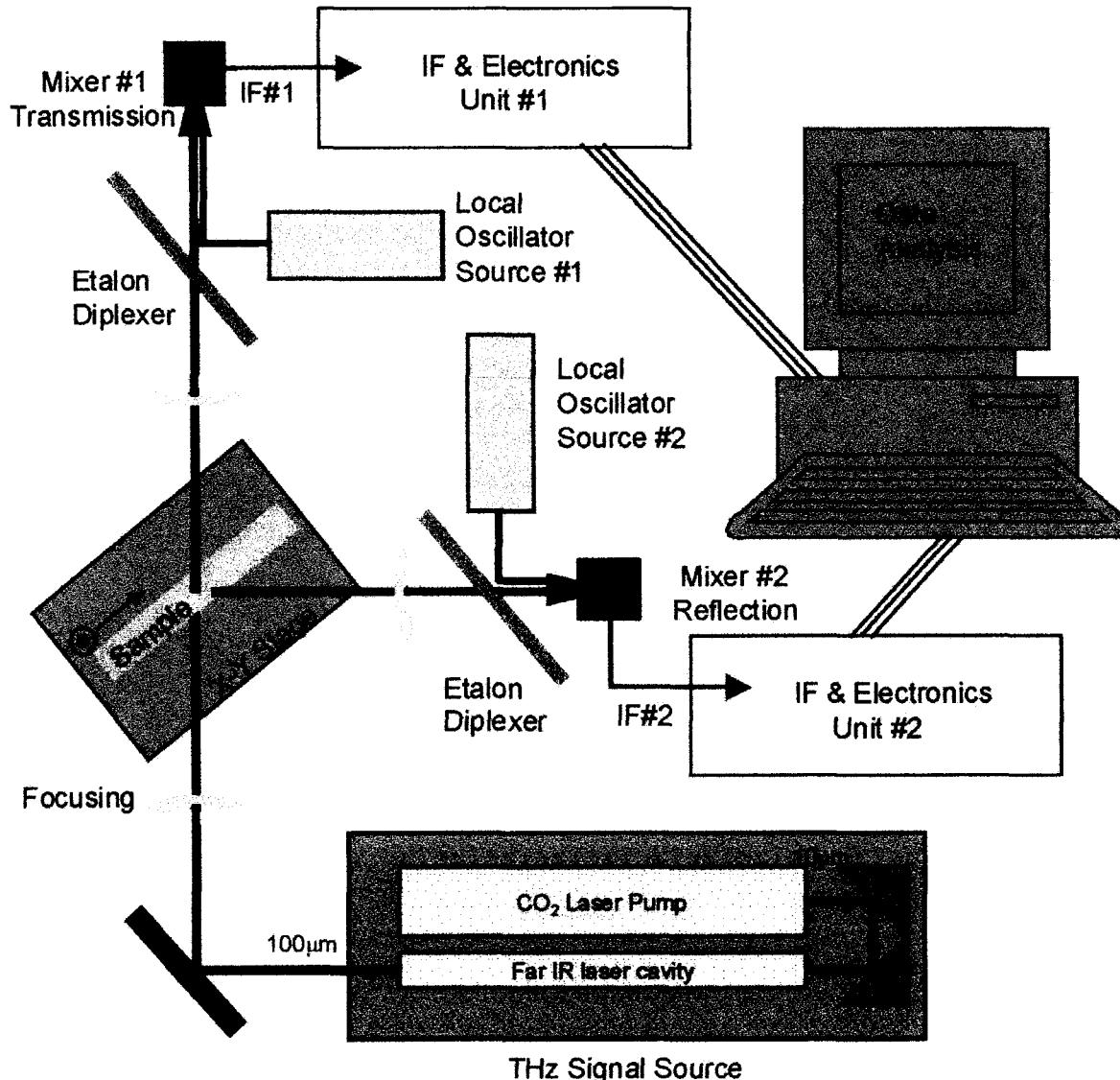


T-Ray image of an extracted human tooth showing identification of a void (cavity) where there exists a change in the time of flight and refractive index picked up by the transmitted THz pulse. (From Don Arnone et.al. , Proc. SPIE, vol. 3823, Munich, Germany, 1999).



*Figure 1. A commercial terahertz imaging system combines many photonic components to enable interesting spectroscopic and image analysis in science, biomedicine, industry, electronics and quality control.*

Commercial T-Ray system from Picometrix. (From: D. Zimdars & J. Rudd, Photonic Spectra, May 2000).



Schematic of a proposed transmission/reflection THz CW biological sample imaging system using a far-infrared laser pump source to generate the mW level signal power that produces significant sample penetration depth and the heterodyne downconverter sensors that provide extremely large sign-to-noise ratio. If the same local oscillator is beam split and used for both receiver channels, phase coherent transmission and reflection measurements are possible, i.e. interference plots.

**DESCRIPTION:**

Application of NASA developed THz heterodyne sensor technology to THz Imaging for space science and biotechnology

**PRODUCT FUNCTION:**

- Provides first ever THz images obtained by high spectral resolution, high sensitivity, ultra wide dynamic range heterodyne system.
- Utilizes both magnitude and phase information to yield tomographic style images of 3D objects
- Simultaneously measures absorption and reflection
- Links NASA and NIH through bio-applications
- >1000 times the penetrating power of existing T-Ray imagers in bio and other material samples

**UNDERLYING TECHNOLOGIES:**

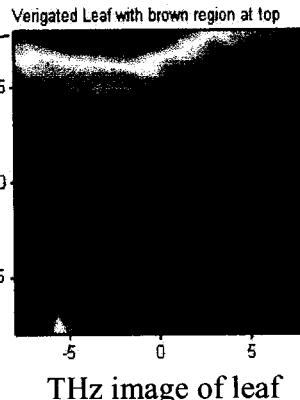
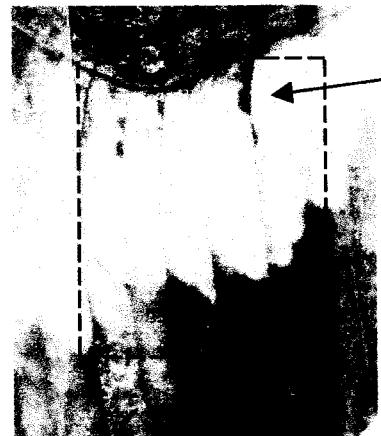
THz semiconductor downconverters, far IR lasers/sources, new image construction and enhancement software

**POTENTIAL USES:**

Characterization of new and existing materials/structures  
Multipixel imaging for greater signal throughput  
Contrast mechanisms in disease diagnosis/material defects

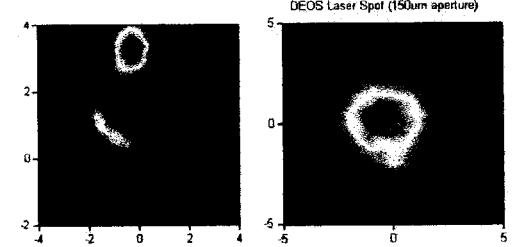
**CURRENT STATUS:**

Initial "proof of concept" direct detection system established to get familiar with issues & capabilities  
Heterodyne system will be assembled pending funding



THz image of a JPL ID badge showing embedded RF coil and transceiver chip for electronic access. The interference pattern is likely Newton rings do to badge curvature.

THz image of DEOS far IR laser beam used to collect data above, before (left) and after (right) proper alignment by Eric Mueller of DEOS.



Monolithically fabricated NANOCONVERTERS for THz RF-to-DC power generation: Convert remotely generated THz RF power to DC for driving nanostructures without wires or batteries!

- Provides direct RF to DC conversion to supply mW of drive power to nanostructures—remotely, without wires.
- Monolithically fabricated and customized to take input at frequencies from 10-10,000 GHz.
- Provides remote power transfer through space or solid structures such as plastics or skin via RF beams.
- Uses nanoscale Schottky diode rectifiers & micron area RF antenna coupling structures for small size/high effic.
- Applications to all field deployable microsystems, THz sensors, bioengineering, nanofabrication, planar antennas

#### UNDERLYING TECHNOLOGIES:

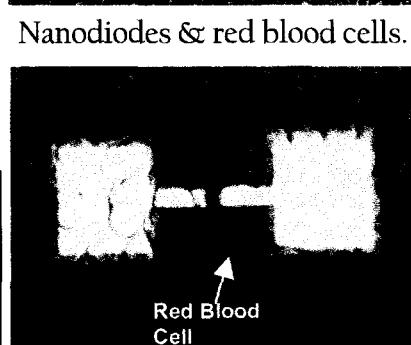
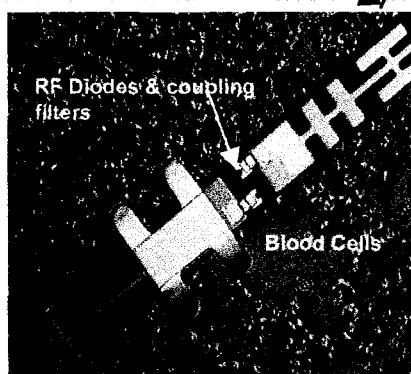
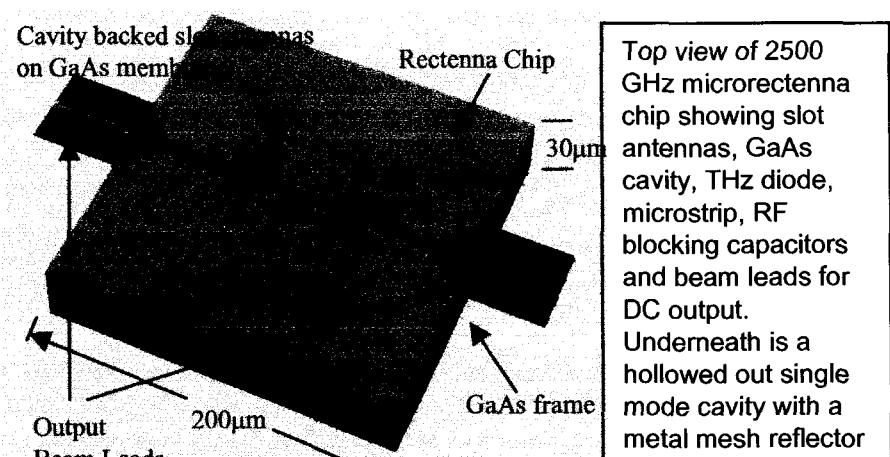
Nanodiodes, THz RF coupling structures, microrectennas

#### POTENTIAL USES:

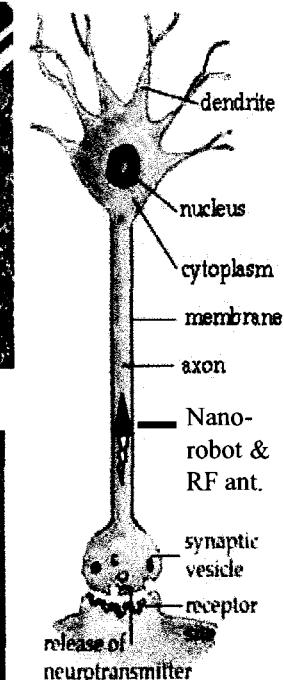
Remote field operation of free space or embedded nanostructures; spatially dispersed multiple target power distribution; high efficiency micron area antennas for communications; highly directional power beaming,

#### CURRENT STATUS:

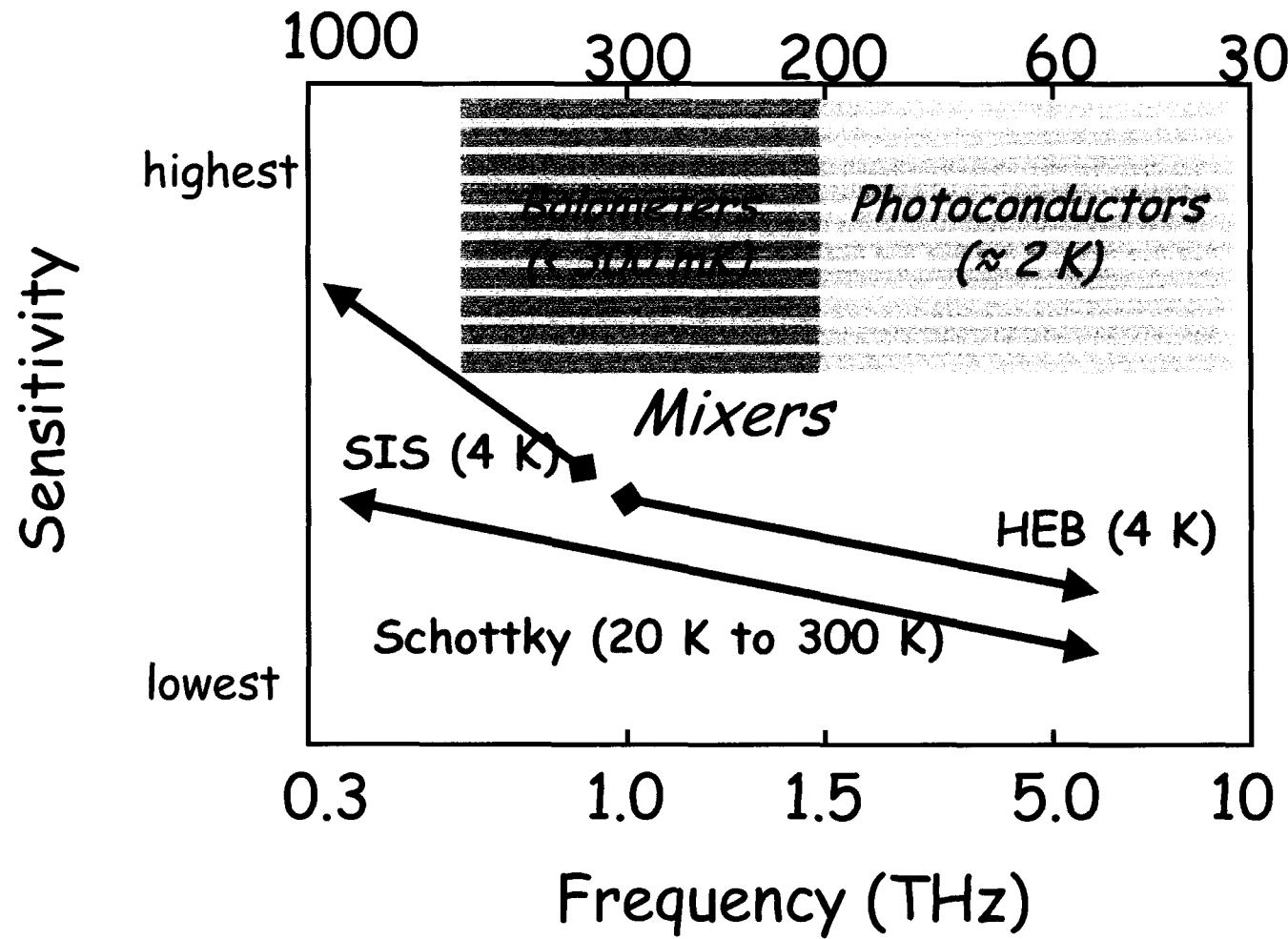
Rectenna concept proven at low freqs. >85% efficiency  
New microrectenna chip designed and in fabrication  
RF sample test system being established



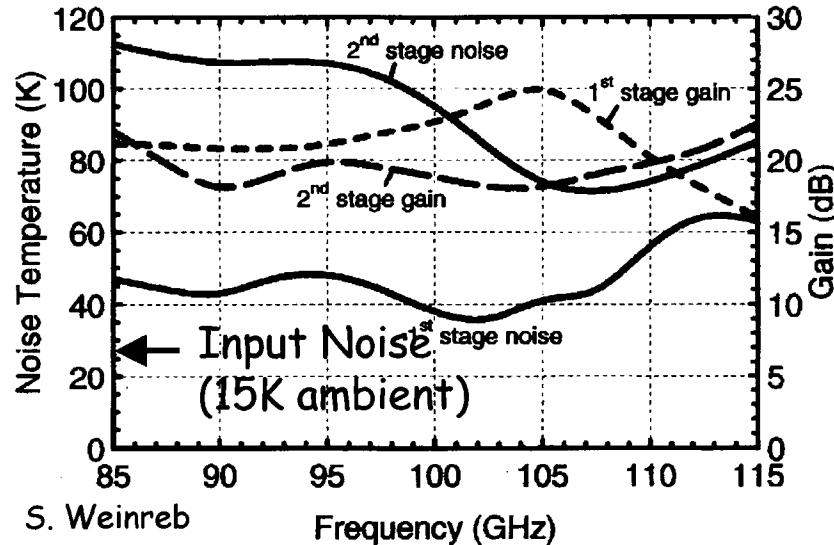
Top view of 2500 GHz microrectenna chip showing slot antennas, GaAs cavity, THz diode, microstrip, RF blocking capacitors and beam leads for DC output. Underneath is a hollowed out single mode cavity with a metal mesh reflector



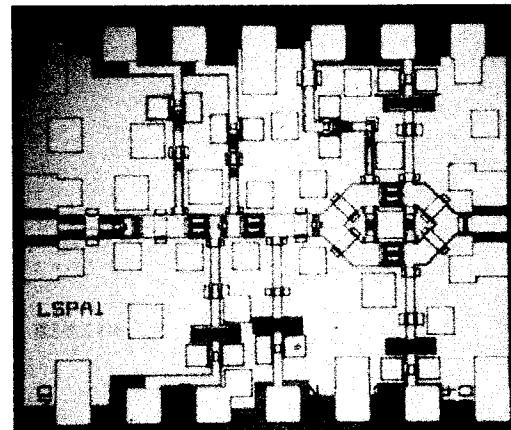
Schematic of a human neuron showing an envisioned nanodevice that might carry tracer chemicals or even neurotransmitters for studying nerve function.



Trade-off space between heterodyne and direct detector technologies in the submillimeter and far IR.  
(From M. Gaidis, 8<sup>th</sup> Int. Conf. on THz Electronics, Darmstadt, Germany, Sept. 2000).

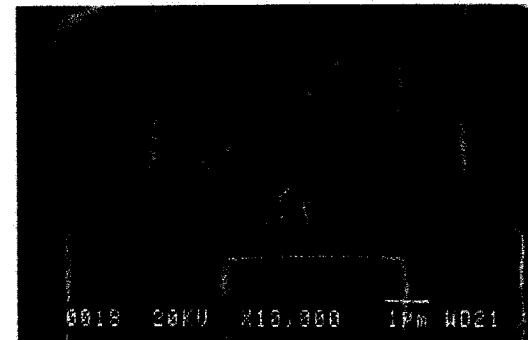


L. Samoska  
& HRL

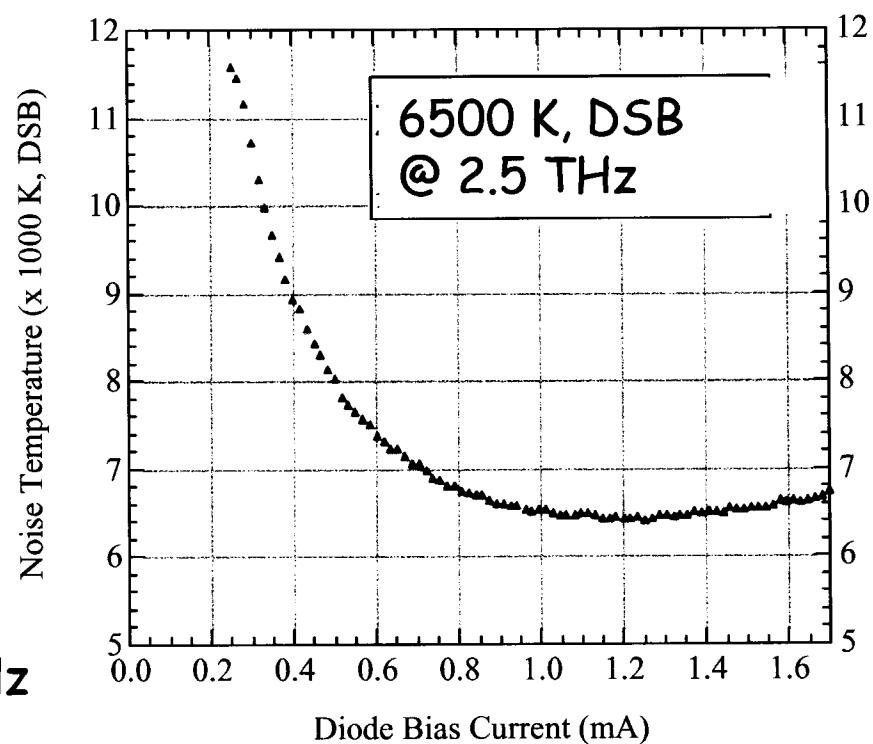


MMIC Amplifiers for 100 - 220 GHz

Slide courtesy M.C. Gaidis - Darmstadt Presentation



Planar  
Schottky  
Mixers to  
2.5 THz





## THz Technology Applications



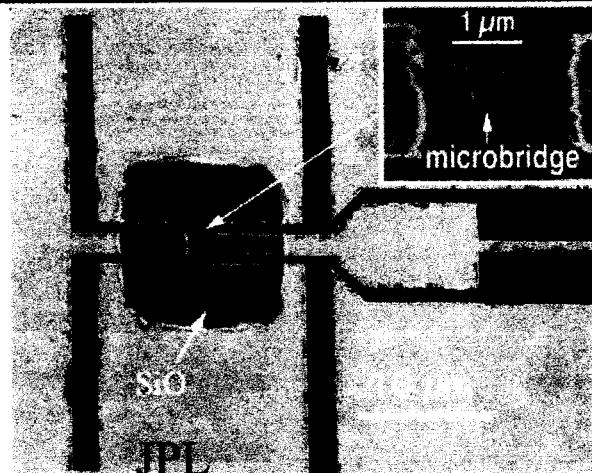
### Performance of Best JPL Flight Mixers and Receivers in Single and Dual Diode Configurations

Program	Frequency		Performance		Mixer Type
	RF	IF	T <sub>mixer</sub>	T <sub>receiver</sub>	
MLS	118 GHz	4-12 GHz	N/A	400K DSB	MMIC Amp
MLS	240 GHz	3-10 GHz	600K DSB	1100K DSB	QUID SHP
MLS	640 GHz	6-18 GHz	2000K DSB	2800K DSB	QUID SHP
MLS	2520 GHz	8-22 GHz	4500K DSB	6500K DSB	MOMED fund.
MIRO	557 GHz	6-18 GHz	2000K DSB	2850K DSB	QUID SHP
Cloud Ice	325 GHz	1-7 GHz	1300K DSB	2200K DSb	QUID SHP
Cloud Ice	450 GHz	1-8 GHz	1700K DSB	2900K DSB	QUID SHP
Cloud Ice	640 GHz	1-10 GHz	1700K DSB	2400K DSB	QUID fund.

QUID=Quartz Upsidedown Integrated Device, MOMED=MONololithic MEmbrane Diode

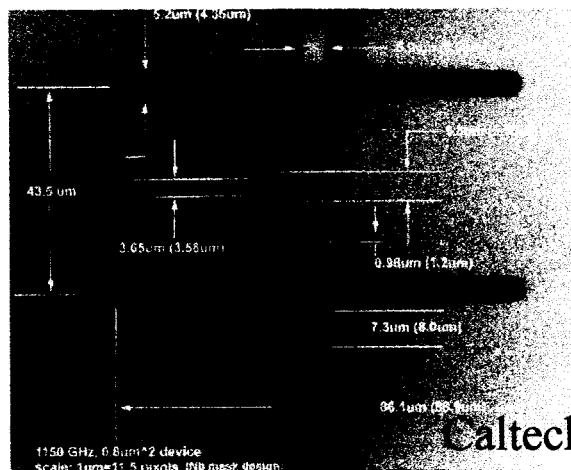


## THz Technology Applications Cooled Heterodyne THz Sensors



Nb HEB @ 4 K  
500 GHz - 5 THz

Quasi-optic coupling  
with twin-slot antennas



Sensitivity:

$$\Delta T \approx T_n / \sqrt{B\tau}$$

for...  $T_n = 1000 \text{ K}$

$B = 10 \text{ MHz}$

$\tau = 1 \text{ second...}$

$$\Delta T \approx 0.3 \text{ K}$$

Interstellar clouds

$\approx 10 - 100 \text{ K}$

SWAS has  
cooled  
500 GHz  
Schottky  
mixers

Source Velocity Resolution:

$$\Delta v \approx c/R$$

for...  $R = 10^6$

$$\Delta v \approx 0.3 \text{ km/s}$$

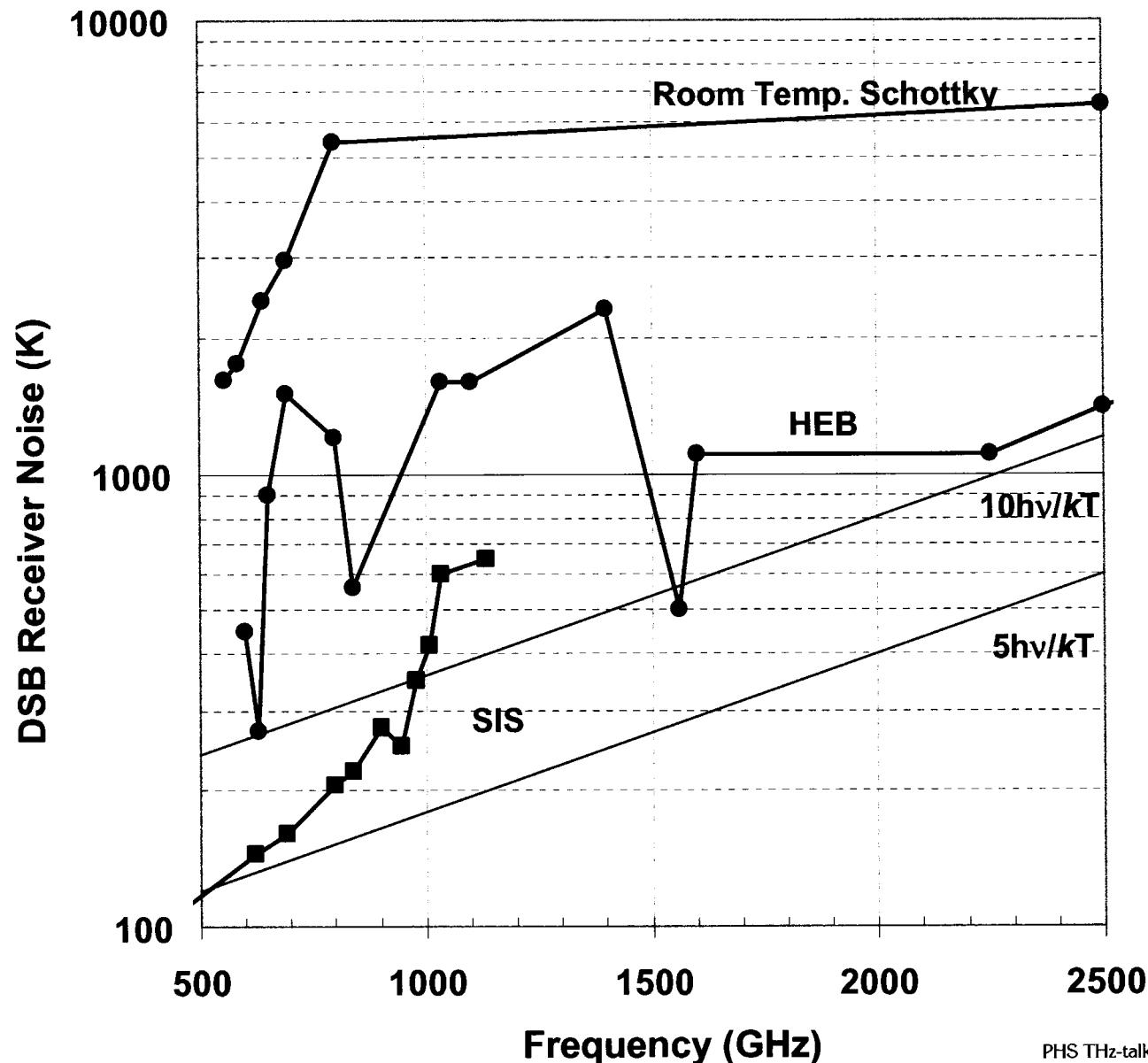
Jupiter & Sun  $\approx 10 \text{ km/s}$

Earth & Sun  $\approx 30 \text{ km/s}$

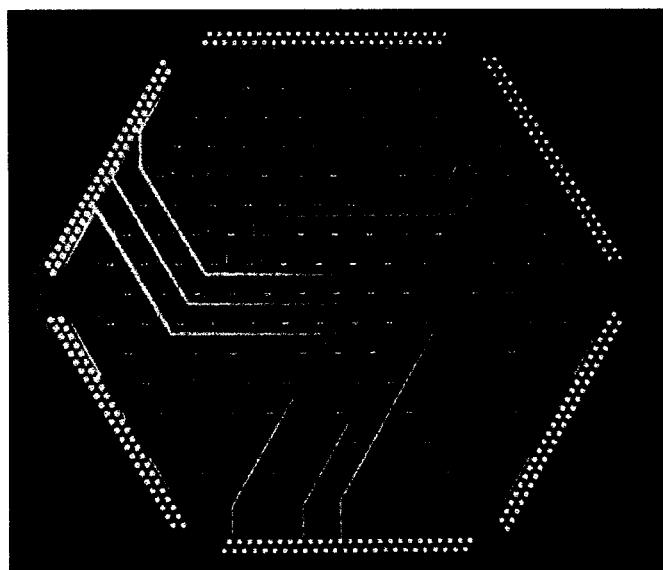
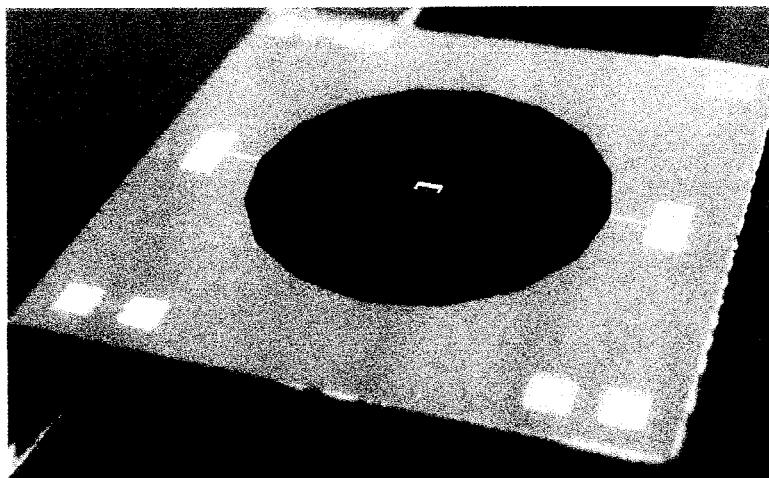
Sun & Milky Way  $\approx 220 \text{ km/s}$

Chart courtesy M.C.  
Gaidis, 8<sup>th</sup> Int. Conf. on  
THz Electronics,  
Darmstadt, Germany,  
September 2000

SIS, NbTiN @ 4 K  
100 GHz - 1.2 THz



## Silicon Nitride Micromesh 'Spider-web' Bolometers



Spider-web architecture

- low absorber heat capacity
- low mass
- low-cosmic ray cross-section
- low thermal conductivity

Sensitivity:

$$\text{NEP} = 1.5 \times 10^{-18} \text{ W/}\sqrt{\text{Hz}}, \text{ at } 100\text{mK}$$

To be used in Planck/HFI, FIRST/SPIRE

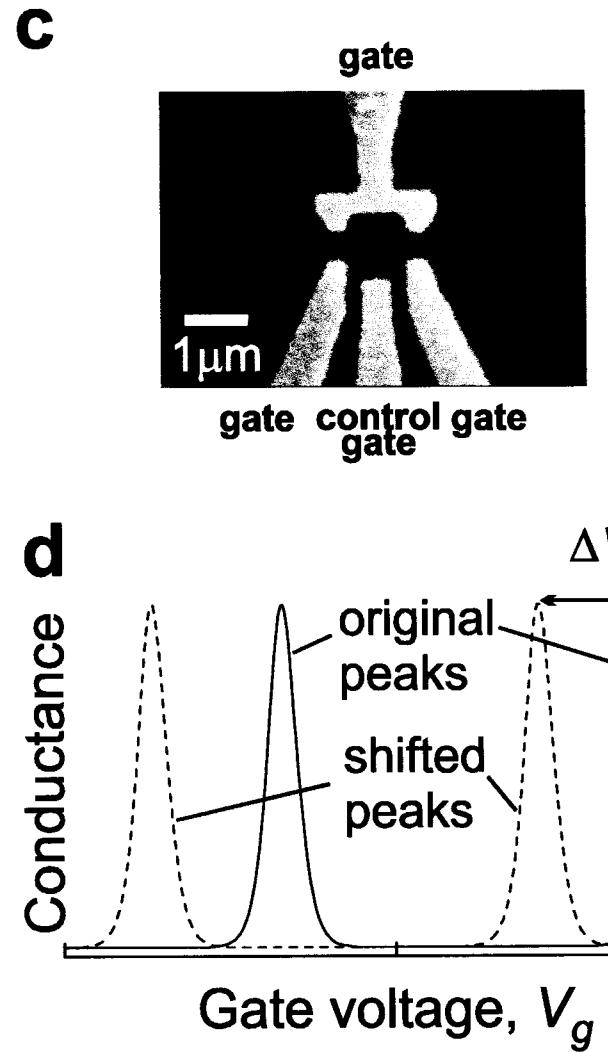
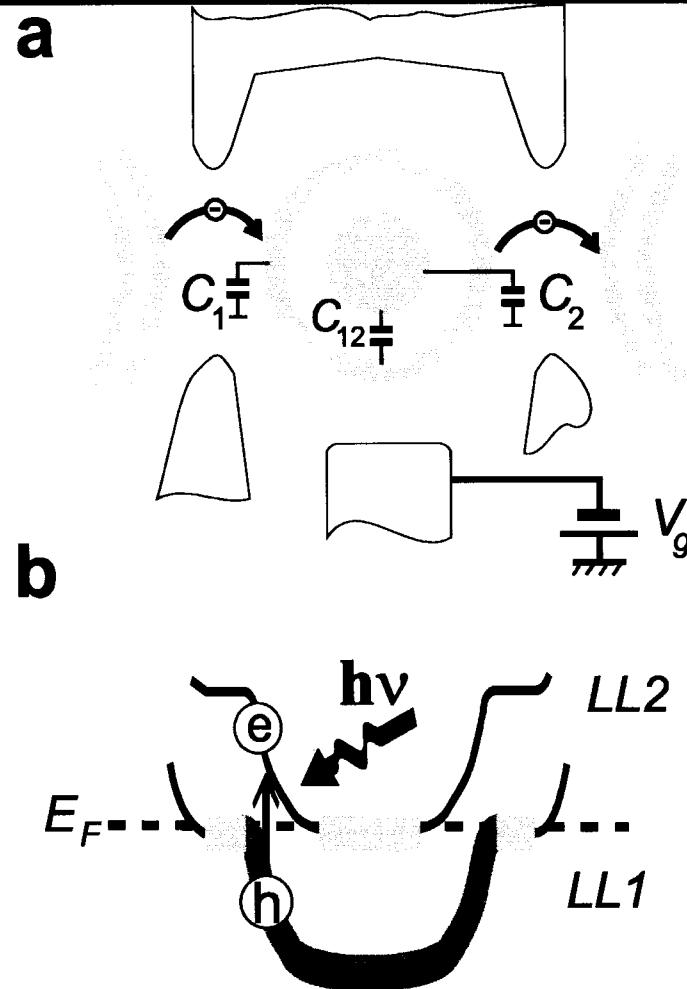
Example:

100 GHz bw, 1 sec integ.,  $10^{-18}$  NEP:

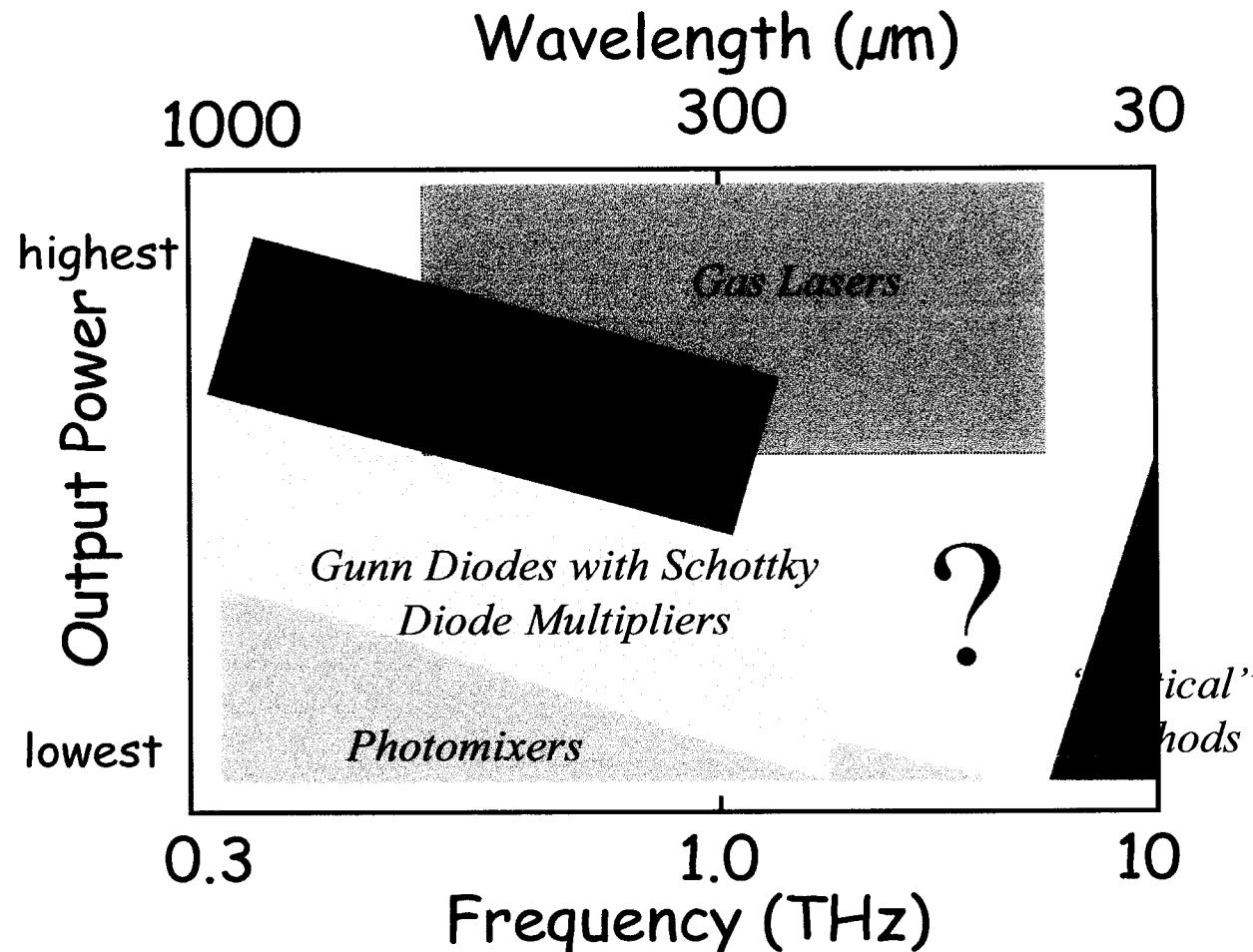
$$\Delta T < 1 \mu\text{K}$$

Chart courtesy M.C.  
Gaidis, 8<sup>th</sup> Int. Conf. on  
THz Electronics,  
Darmstadt, Germany,  
September 2000

Work by Jamie Bock, JPL



The Komiyama quantum-dot single-photon detector (From S. Komiyama et.al., Nature, v. 405, Jan. 27, 2000)

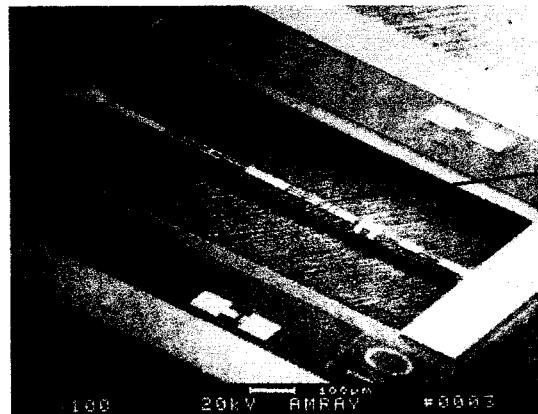


Artificial sources of THz power. The low end of the power scale represents nanowatts, the high end mW.  
(From M. Gaidis, 8<sup>th</sup> Int. Conf. on THz Electronics, Darmstadt, Germany, Sept. 2000).

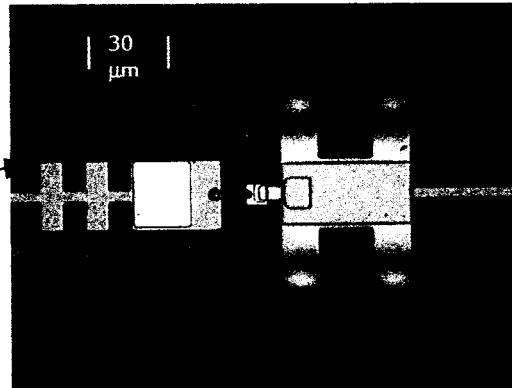


# THz Technology Applications

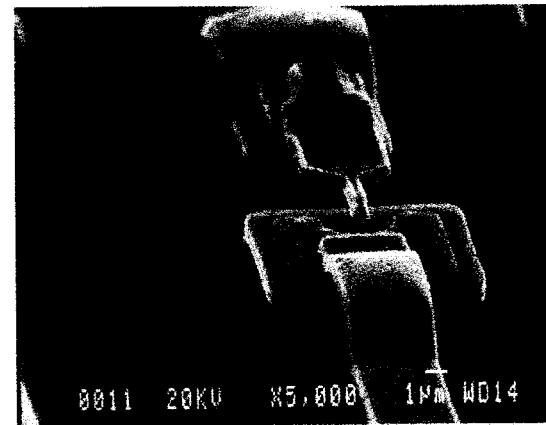
## Monolithic THz Mixer and Multiplier Devices



MOMED tripler circuit for 2.7 THz

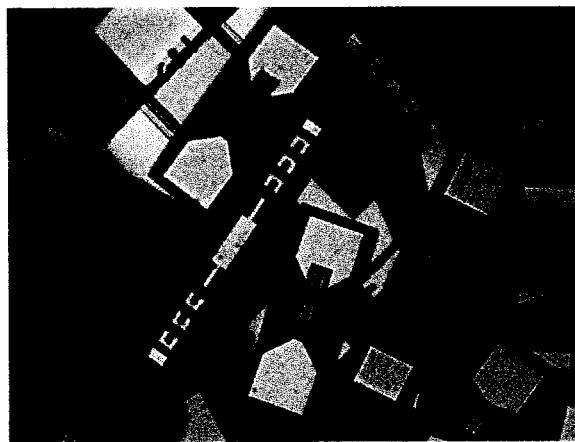


MOMED device blowup.  
Anode is 0.1x0.5 microns!

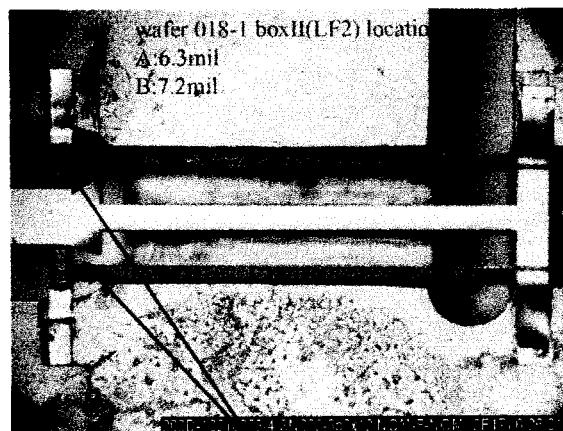


0011 20KV X5,000 1nm WD14

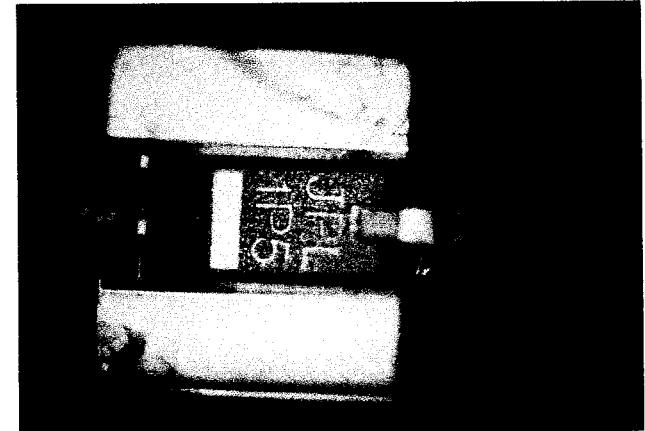
JPL Monolithic Membrane Diode (MOMED) process for ultra high frequency Schottky mixers and multipliers



JPL Submm-λ GaAs membrane circuits



100-200 GHz 6 diode, drop-in doubler  
yielding 50% efficiency and 25mW



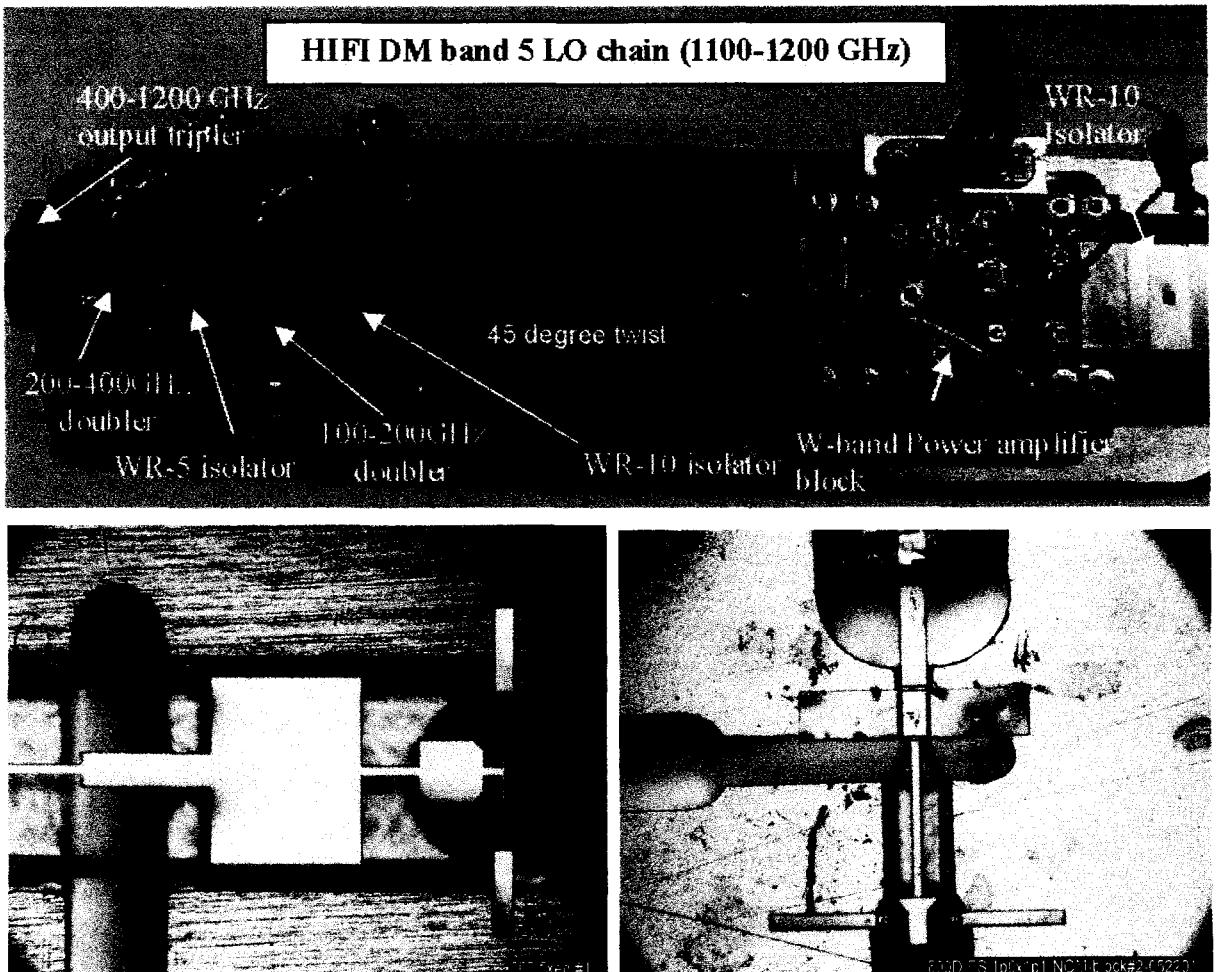
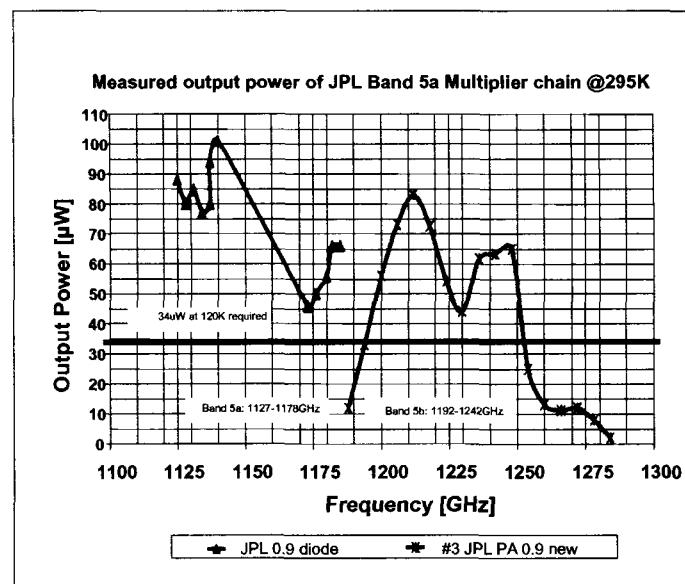
1200 GHz tripler circuit on GaAs membrane

Sponsors: CodeR, Code Y (EOS-MLS), Code S (FIRST)

Device work by: I. Mehdi, J. Gill, S. Martin, B. Nakamura, A. Fung, M. Dickie, T. Jun - JPL

### Recent Amp/Multiplier Performance

- Power Amps: 400mW at 94GHz; 200mW 90-105 GHz; 40mW 65-145GHz; 15mW with 85-90 GHz VCO, 20mW 145-170 GHz (HRL)
- Multipliers: >20% efficiency & 9mW from 200-400 GHz (doubler);
- 2 mW @ 800 GHz (double-doubler)
- >250 $\mu$ W @ 1200 GHz (cooled tripler)
- 0.1  $\mu$ W @ 2500 GHz (tripler)



Work by SWAT LO Team: Imran Mehdi, Frank Maiwald, Alain Maestrini, Erich Schlecht, Goutam Chattopadhyay, Dave Pukala, Ray Tsang, John Gill, Suzi Martin, William Chun, Brad Finamore, Lorene Samoska and HRL (VCO), TRW (power amps)



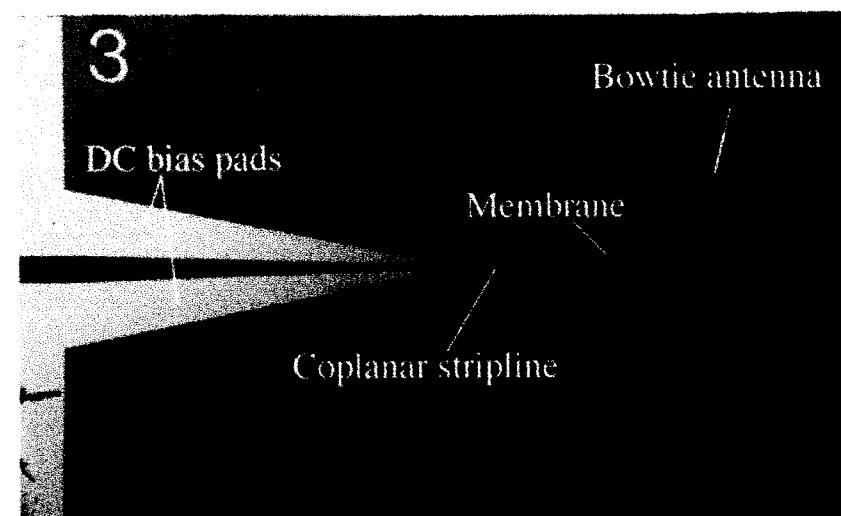
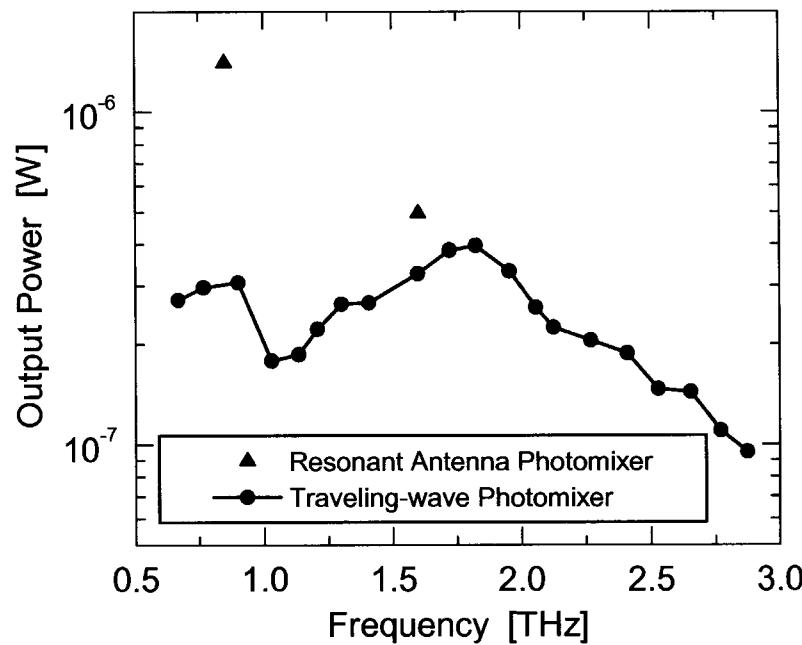
# THz Technology Applications

## JPL & Contracted Flight Local Oscillator Sources



Program	Frequency		Performance		LO Type
	Pump	Output	Pwr Out	Eff.	
MLS 240	120 GHz	120 GHz	6 mW	2W	Locked InP Gunn (Quinstar)
MLS 640	107 GHz	321 GHz	4 mW	8.0%	Dual diode Gunn + Tripler (RPG)
MLS 2520	2520 GHz	2520 GHz	20 mW	75W	CO <sub>2</sub> + CH <sub>3</sub> OH Laser (DEOS)
MIRO	139 GHz	278 GHz	7 mW	20%	InP Gunn + Doubler (UMass)
Cloud Ice	81 GHz	162 GHz	6 mW	7.5%	DRO+AMP+Doubler (JPL)
Cloud Ice	112 GHz	224 GHz	6 mW	8.0%	DRO+AMP+Doubler (JPL)
Cloud Ice	107 GHz	640 GHz	0.4 mW	1.0%	InP Gunn+X2+X3 (RPG)
FIRST	100 GHz	200 GHz	50 mW	25%	Amp+Doubler (JPL)
FIRST	200 GHz	400 GHz	10 mW	20%	Doubler (JPL)
FIRST	400 GHz	800 GHz	1mW	12%	Doubler (JPL)
FIRST	100 GHz	800 GHz	2mW	1.3%	Full X8 chain at 120K (JPL)
FIRST	400 GHz	1200 GHz	80 μW	1.0%	Tripler (JPL) [1200-1250]
FIRST	400 GHz	1200 GHz	250 μW	0.8%	Tripler at 120K (JPL)

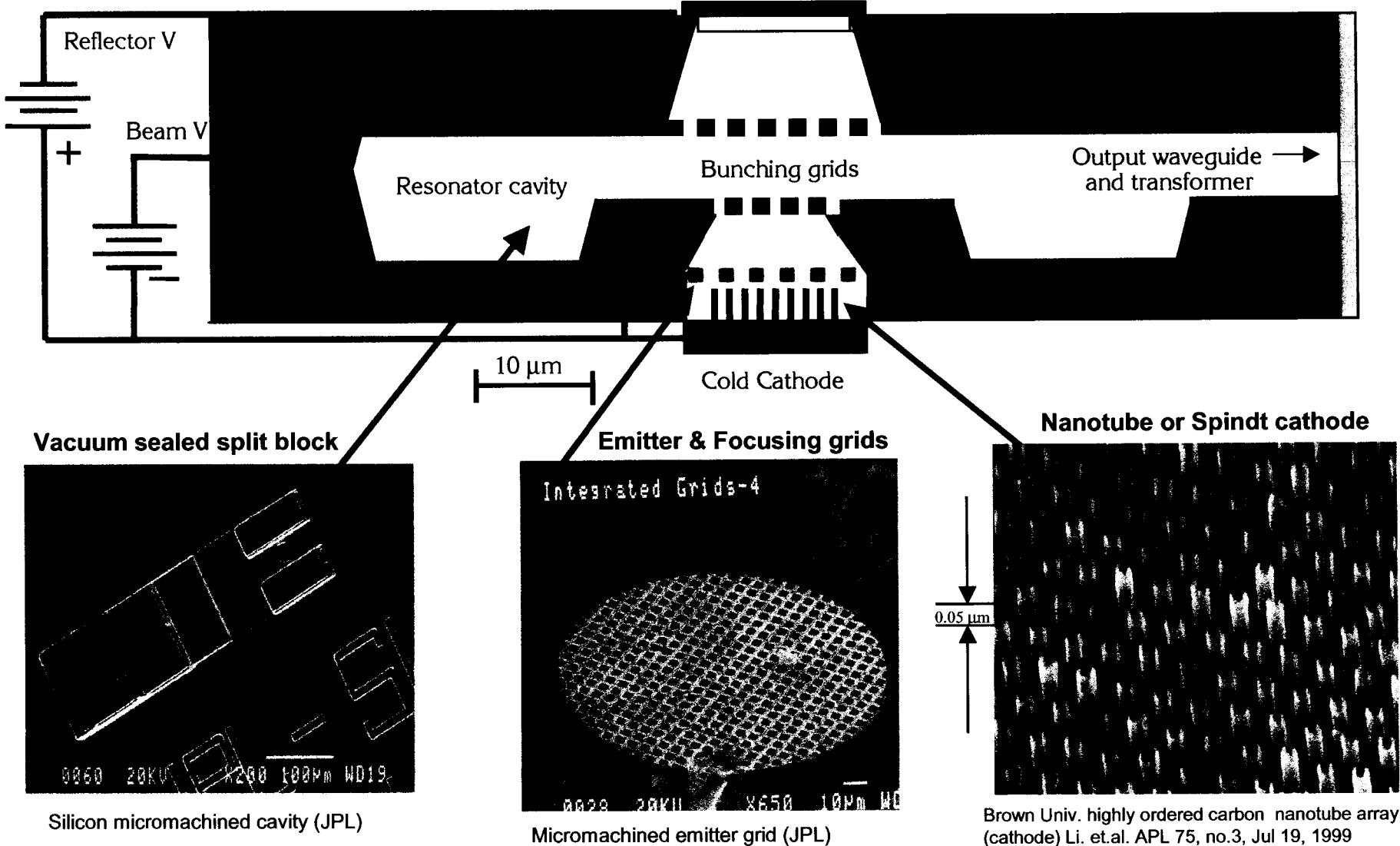
- Membrane-supported, or arrayed-antenna distributed gain region:
  - Low RF losses, high output power, avoid thermal burn-out
- Novel materials for  $1.55 \mu\text{m}$ : GaAs:ErAs and InAlGaAs:ErAs



Collaboration of: JPL, UCSB, Caltech- Rolf Wyss,  
Andrea Neto, Pin Chen, John Pearson

Courtesy of R. Wyss

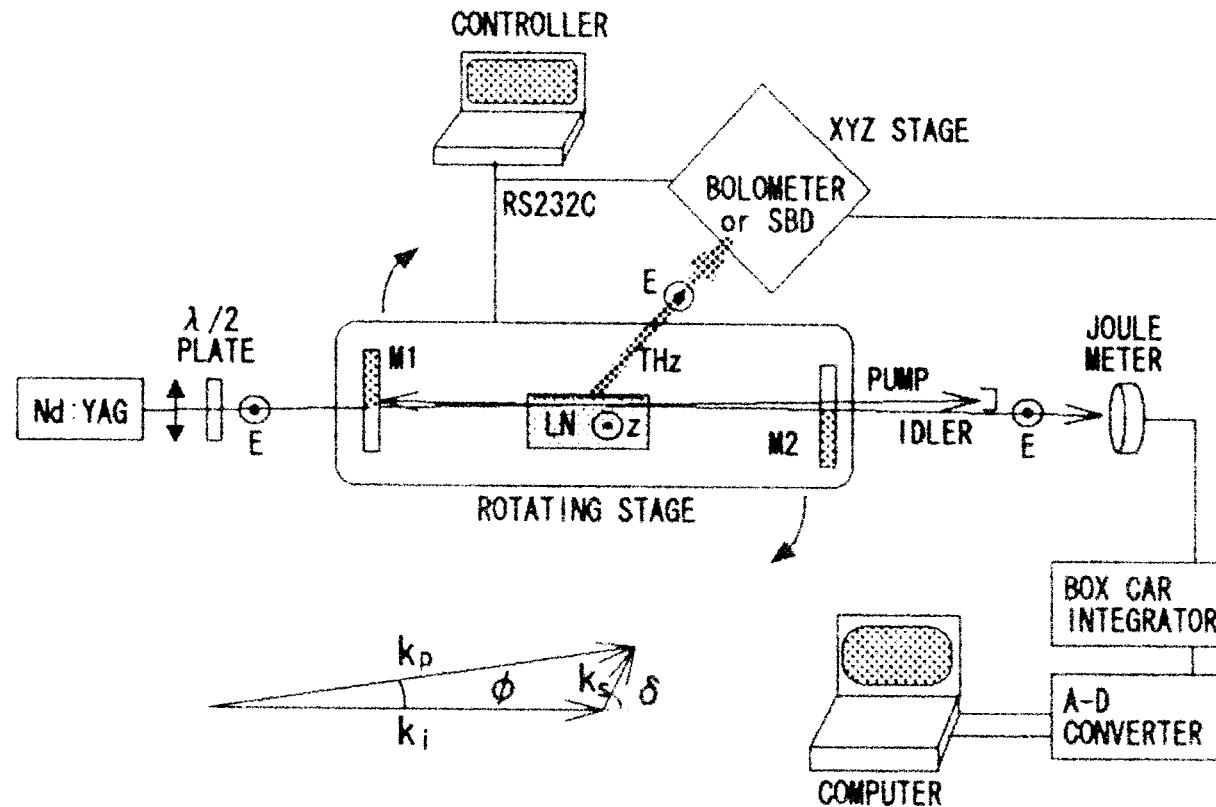
### SCHEMATIC CONSTRUCTION WITH REALIZED STRUCTURES



Silicon micromachined cavity (JPL)

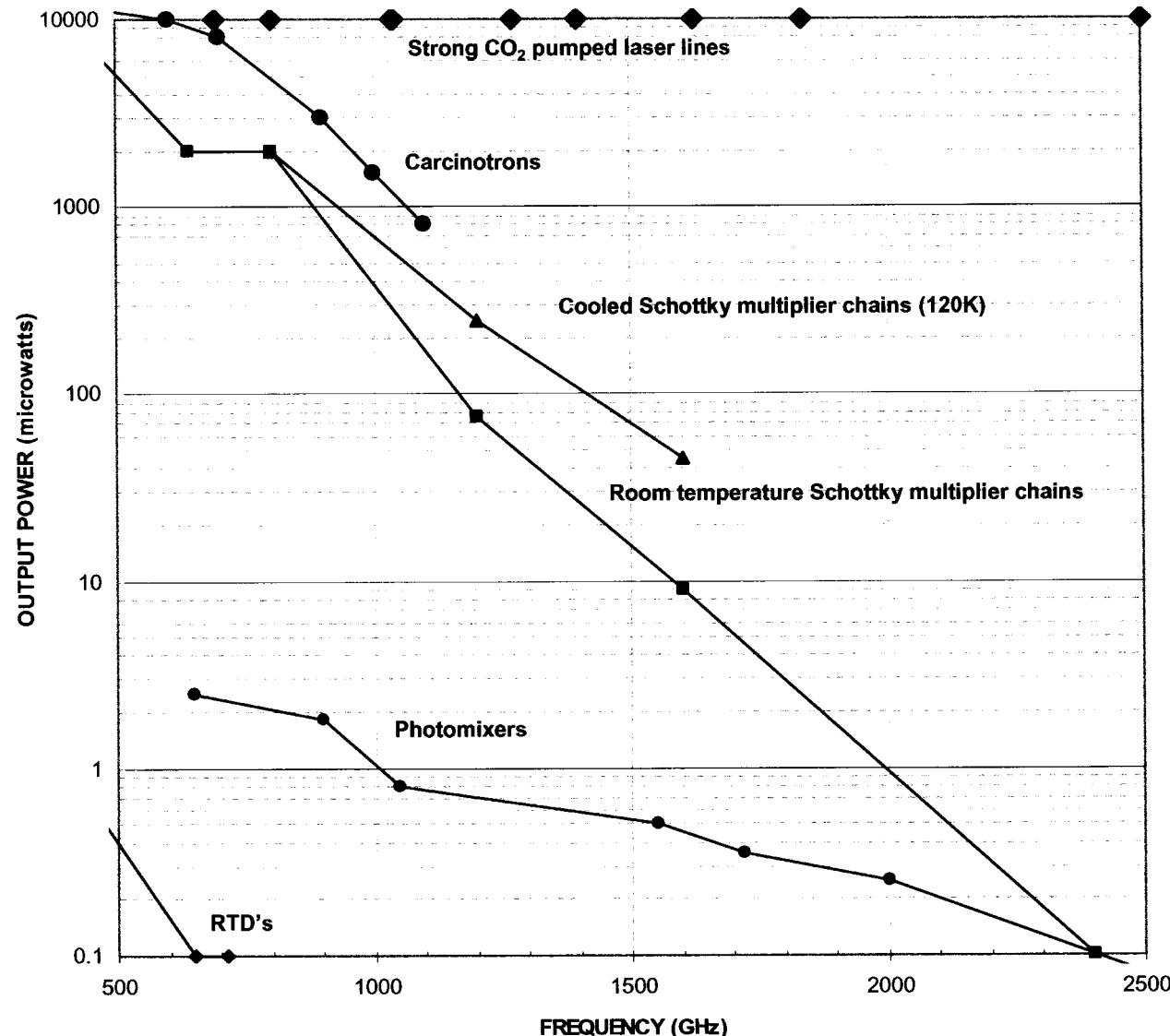
Micromachined emitter grid (JPL)

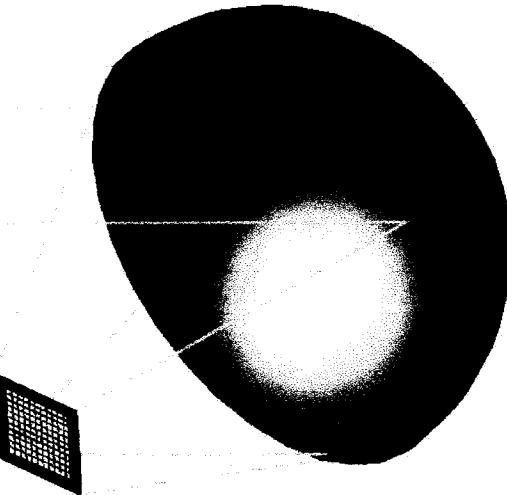
Brown Univ. highly ordered carbon nanotube array (cathode) Li. et.al. APL 75, no.3, Jul 19, 1999



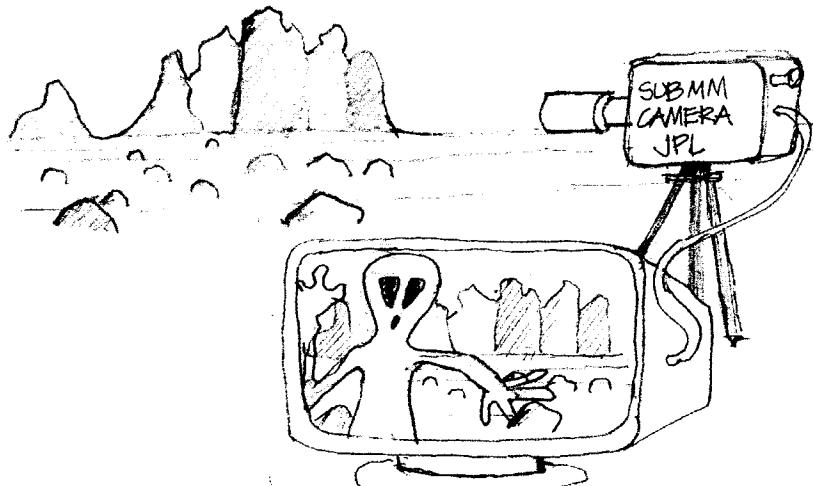
**Terahertz generator based on laser illumination of a lithium niobate crystal**

(K.Kawase, M. Sato, T. Taniuchi and H. Ito, "Coherent tunable THz-wave generation from LiNbO<sub>3</sub> with monolithic grating coupler," Appl. Phys. Lett., vol. 68, no. 18, pp. 2483-2485, April, 1996)

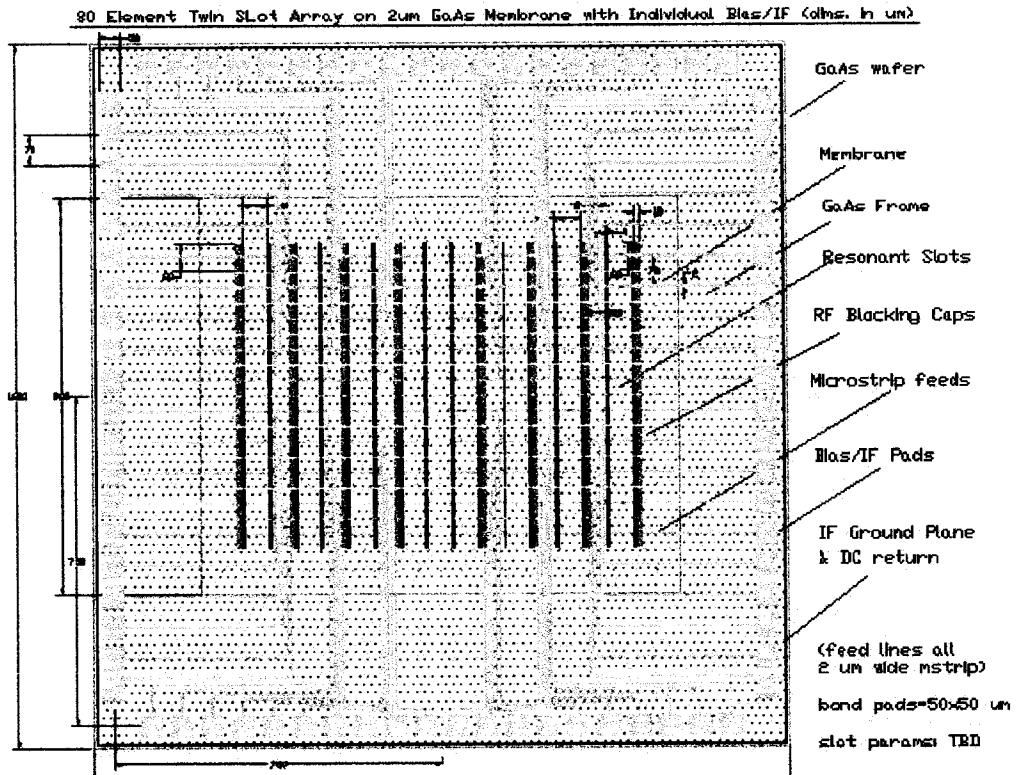




THz camera front-end used together with an off-axis parabola for beam focusing/shaping.



### Submillimeter-Wave Camera



2.5 THz 80 Element Slot Array Chip with Individually Addressed Heterodyned Outputs and Bonded in IF amplifiers for Imaging



## THz Technology Applications SUMMARY



- Due to recent component advances, THz technology is finally ready to move into applications. It is one of the last untapped regions of the electromagnetic spectrum, and offers the promise of unexplored usefulness and unanticipated discoveries.
- Past applications for THz technology and instruments have primarily focused on spectroscopy, astrophysics and planetary and Earth remote sensing, however sporadic sojourns into other fields dot the literature.
- Despite tremendous gains in the detector area, the same limitation which has hampered THz development for the last 35 years continues to dominate the attention of researchers: THz sources.
- As we accumulate more THz component technologies, we will begin to be able to realize a much wider variety of instruments and an expanded application base. The biomedical applications promise to introduce THz technology to the general public for the very first time.
- Finally, with higher levels of device, circuit and antenna integration, high sensitivity *THz imaging* – the (my) holy grail of THz technology – will open up a whole new window of opportunity for this yet-to-be-exploited spectral range.